FREE FIELD CALIBRATION OF HYDROPHONES & PROJECTORS : "REPEATABILITY" IN ACOUSTIC CALIBRATIONS

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1. INTRODUCTION

The purpose of an Underwater Acoustic Calibration Facility is to accurately provide a reliable and efficient calibration service for its clients. In order to provide this service, the facility must make provision for, and uphold a set of quality procedures which ensure that a client is provided with a detailed set of results which describe the characteristics of an unknown transducer (under stated conditions which simulate those of the operating conditions as closely as possible) together with an accurate assessment of the uncertainties attributable to each measurement of the device under test. The accuracy of these results is of paramount importance and to achieve this aim necessitates the use of demonstrably valid methods and procedures.

Every effort must be made to minimise the uncertainties present within a calibration system. For a facility providing an external calibration service, this should be independently audited on a regular basis and a pre-requisite must be having measurements traceable to National Standards. Customer confidence in the quality of the calibration results will be achieved by the knowledge that the uncertainties attributable to procedures and random errors have not been under estimated.

A successful calibration is therefore founded in confidence placed on procedures, equipment and computer software where used. If procedures are correctly followed, calibration variations will be reduced to a minimum and accurate calibrations will be repeatable, by any operator, using any assigned and calibrated equipment, with no changes expected over time and conditions, other than those which are an attribute of the device itself.

Repeatability of a measurement does not guarantee accuracy as it is not a difficult matter to repeatably calibrate a device incorrectly. Repeatability creates confidence that the embodied procedures are both being followed and are suitable for their task. This paper examines how these factors are tackled by Marine Acoustics Ltd at the MOD NAMAS accredited Underwater Acoustic Calibration Centre. We describe the facility and the procedures used and demonstrate how standards of repeatability and accuracy are monitored and maintained. This is presented with a number of results which demonstrate how confidence is upheld through long term repeatability of results.

2.THE ACOUSTIC CALIBRATION FACILITY

The facility is an open water site located at the Thames Water Wraysbury Reservoir (2.25km x 1km). The floating calibration laboratory (30m x 18m) is bottom tethered and reached by boat. The reservoir banks are sloped (at 18°), the nearest being 300m from the laboratory and so reflections from the sides of the reservoir are negligible. Directly under the laboratory the water has a depth of 20m. Calibrations are performed at a depth of 5m, in pulsed mode to eliminate surface & bottom reflections. Over the accredited frequency range of 1 - 350 kHz, the site has the enviable position of operating in a true free field environment, working in pulsed mode operation.

The laboratory has three pairs of hoist stations - one fixed and one rolling to give adjustable separation between transducers of up to a maximum of 12.5m. (By using two fixed hoist stations, a maximum separation of 24m can be achieved). Each rolling station has four calibrated reference transducers covering different frequency ranges which gives an overall accredited frequency range capability of 1-350kHz. The maximum lifting capability of each station is 1.5 tonnes. Although the site has NAMAS accreditation over a set frequency range, extensions of these ranges are occasionally demanded; non-accredited calibrations can therefore be performed over bands above and below that stated. Another useful feature available is the capability to test transducers under extended pressure in a controlled environment. Using a 2 x 3 metre fibre glass pressure vessel, pressures up to 500 psi (35 bar) can be achieved. The facility as a whole offers considerable versatility over the type of measurements performed and type of device which can be calibrated : this is reflected in the popularity of the site for both commercial and defence customers throughout the world.

2. CALIBRATION PROCEDURES

Calibrations are carried out by comparison or reciprocity, depending on the customer's requirements. Reciprocity arrangements provide the most accurate means of calibration currently available, but are generally time consuming. Comparison calibrations are an efficient and accurate means of calibration[1] which are sufficient for most needs, however this type of calibration can only be used successfully if the comparison devices are routinely subjected to strict re-calibrations : this is all the more important for an open water device, where the transducers will be subject to considerable temperature variations over the year, which can promote small yet significant excursions from a calibrated sensitivity. Calibration of the laboratory reference standards themselves are discussed later and are a primary calibration, traceable to national standards, thus, calibration of a customers device is taken directly from a true primary standard.

2.1 INTERNAL CALIBRATION

To achieve the level of accuracy required for the customer, the basic measurements of the physical characteristics of each of the in-house projectors must be carried out as accurately as possible using fully documented and accepted procedures. Each of the reference transducers (four per station) is calibrated using a reciprocity technique which gives an absolute characterisation of the device.

One of the benefits of operating in an open water site is that transducers can be calibrated in an environment which much more closely matches that of it's intended usage. However this brings with it the variability of the ambient water temperature over the year : 2°C to 20°C. As this is quite a considerable temperature variation, significant changes in the performance of transducers can be expected [2]. Figure 1 shows a typical example of the difference in calibration between measurements taken in Summer and those in Winter, as can be seen there are -2 dB and +1dB differences which are quite obvious. Quite clearly the standards used for comparison purposes need to be regularly calibrated to keep any excursions within 0.5dB. Calibrations of the reference transducers are therefore performed four times per year, triggered by a 4.5°C change in water temperature. Measurement uncertainties quoted on the calibration results are based on the temperature of the measurement being within 4.5°C of the temperature of the reference transducer calibration. Due to workload demands or a quick change in water temperature due to the weather, it is not always possible to perform a trimetric calibration before the water temperature has changed by more than 4.5.C In this situation, the measurement uncertainties quoted on the calibration results are automatically increased accordingly by the software.

Although trimetric calibrations performed at different water temperatures give different sensitivities for the reference transducers, they compare very well with previous ones performed at a similar

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temperature. A typical comparison of calibrations is shown in Figure 2, two calibrations are compared at 7°C for the rising temperature before Summer and the falling temperature before Winter. The correlation here is quite impressive, with less than 0.2dB variation over the entire frequency range. This ability to repeat measurements under similar conditions by varying equipment and personnel lends confidence in the calibration and measurement procedures and greatly enhances the long term status of a site's abilities.

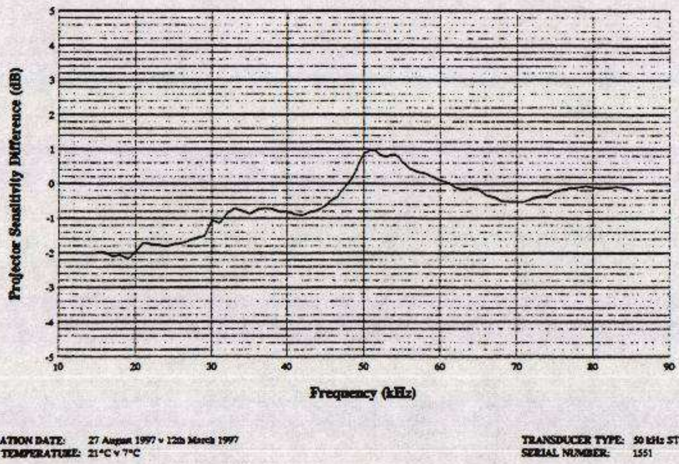

Figure 1 : Comparison between 'Summer' and 'Winter' reciprocal calibrations of the 50 kHz standard transducer. Temperature difference = 14°C

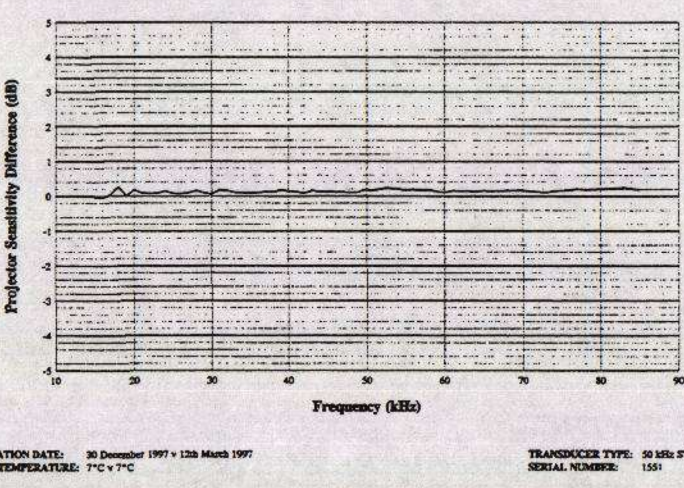

Figure 2 : Isothermal comparison between 'rising' and 'falling' reciprocal calibrations of the 50 kHz standard transducer. Calibration Temperature = 7°C

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2.2 JOB CALIBRATION

The sensitivity of the device under test is measured over the required frequency range using one or more of the calibrated acoustic reference standards. In general, the hydrophone sensitivity of a device is measured and then converted to projector sensitivity via the measured admittance data. The unknown transducer is mounted on a fixed hoist station and the reference transducers are mounted on the rolling station to give a variable separation. The runway tracks for rolling stations have distance markers for accurate positioning. The separation is set to at least the minimum that is required to give far field conditions according to the size of the transducers and the maximum frequency of calibration (Equation 1)[3]

$$d = \frac{a^2}{\lambda} \qquad \text{Equation 1}$$

The transducer is wetted with detergent and soaked (ideally) overnight at depth to stabilise. (The reference transducers are kept underwater permanently.) Calibrations are usually performed at a depth of 5m, but at low frequencies where surface reflections may start to have an effect, the depth can be increased to approximately 6.5m by use of a longer mounting bracket.

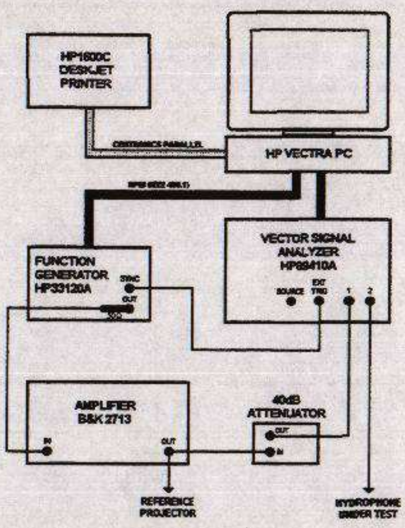

Figure 3 : Schematic diagram of calibration equipment

2.3 CALIBRATION EQUIPMENT

All of the calibration procedures are under computer control, a schematic diagram of the main components is shown in Figure 3. A Hewlett Packard(HP) HP4192A Impedance Analyser (not shown) is used for measuring admittance data. For measurement of hydrophone or projector sensitivities, an HP33120A Function Generator generates pulses (tone bursts) which are fed through a B&K 2713 amplifier (monitored via a 40dB attenuator). The output is fed directly from the amplifier to the standard appropriate to the frequency range being used. As noted above, for most general calibrations, the device under test is used as a hydrophone, with projector sensitivities being derived from the initial admittance measurements. The output from the unknown transducer is fed to a HP89410A Vector

Signal Analyser (VSA) which performs the measurements, the output from this being fed back into the control equipment. This consists of an HP Vectra PC running in-house written software, running under HP BASIC for Windows.

2.4 CALIBRATION SOFTWARE

As has been mentioned, much of the laborious procedures of transducer calibration are undertaken by computer using specifically written software. Data collection and processing is carried out by this aspect of the laboratory, in association with the functions offered by the VSA.

When a trimetric calibration is performed on the reference transducers, the hydrophone and projector sensitivities and the temperature of the water during the calibration are stored in a file to be recalled during the calibration of the device under test.

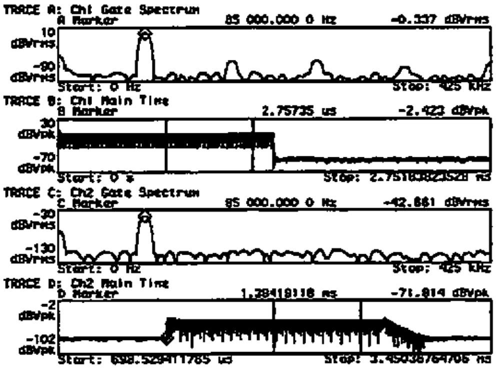

Figure 4 : Screen shot of typical VSA gating procedure.

Hydrophones are calibrated by projecting from a reference transducer in pulse (tone-burst) mode. To eliminate surface reflection effects, the pulse length at each frequency is set automatically by the software according to the depth and separation. This is not always possible at low frequencies due to the long wavelengths, and so the effect of surface reflections is estimated using the vertical directivity of the reference transducer, and the measurement uncertainties are increased accordingly. The low frequency reference transducer is a seven element stave, and so is not omni-directional in the vertical plane even down at 1kHz. The directivity of this device is calculated from the theoretical beam pattern and observed polar plots. Both the transmit and receive pulses are captured by the Vector Signal Analyser. The software searches for the start of the receive pulse and sets the measurement gate far enough into the pulse to avoid turn-on transients (at least 5 cycles). A typical screen shot from the Vector Signal Analyser is shown in Figure 4. The time traces are displayed in logarithmic magnitude format (i.e. the bottom half of the waveform is flipped positive, the amplitude then being converted to dB). This conversion allows the software to find the start of the pulse much more accurately. The measurement gate is a least 4 cycles long (depending on the length of the pulse) to maintain measurement accuracy, and is set the same distance into the pulse for both the transmit and receive signals. The VSA then performs a FFT on the signal within the gate and returns the levels of the signals at the measurement frequency. Five measurements are made at each frequency and the difference between the minimum and maximum of these has to be within a user-set limit (typically 0.5dB) for the measurements to be accepted; if not, another set of five measurements are made. The hydrophone sensitivity is calculated from the average of these measurements.

The reference transducers are generally driven using a 1Vrms output from the function generator and 40dB gain set on the B&K amplifier (i.e. 100Vrms into the reference transducer). But when calibrating hydrophones with built-in preamplifiers, high source levels may cause the pre-amplifier to overload. In this situation a limit can be set for the sound pressure level at the hydrophone, and the software automatically adjusts the function generator output at each frequency according to the reference transducer projector sensitivity and the separation.

3. UNCERTAINTIES

These are estimated according to the methods in NAMAS publication M 3003 [4]. Sources of uncertainty which have been taken into account include accuracy of measuring instruments, alignment of transducers, accuracy of separation distances, fluctuation of signal during measurement, accuracy of trimetric calibrations, the temperature drift of the reference transducers and, at low frequencies, the effect of surface reflections. The effect of surface reflections can often be made insignificant by increasing the depth and reducing the separation as much as possible while still remaining in the far field. It is not always possible when calibrating large transducers or ones with limited cable length.

3.1 SYSTEMATIC UNCERTAINTIES

These account for a significant part of the overall accuracy of any measurement and the appropriate choice of equipment, procedures and software will ensure that the quality of the results achieved will meet the intended measurement accuracy. The actual value of the uncertainty is estimated using guidelines published in the M30003 [4], and the reader is referred there for further information.

In the calculation of the measurement uncertainty, the accuracy of the measuring instrument is taken to be that quoted in the manufacturer's specification, however, the results quoted often show that its accuracy is well within that quoted in the specification, hence these inaccuracies are generally over-estimated.

The value used for the temperature drift of the reference transducers is based on the maximum drift seen for each type of transducer over years of trimetric calibrations. This value is used for the entire frequency range of the transducer, even though as can be seen from the comparison graphs in Section 2, the temperature drift is generally significantly less than this and at certain frequencies negligible. Whilst ideally the temperature drift should be estimated for each frequency, this is not practical as it takes years of trimetric calibrations to build up a picture of a transducer's temperature characteristics and from experience, maintenance work on the transducer can cause these characteristics to change.

3.2 RANDOM UNCERTAINTIES

After due appreciation of all systematic uncertainties, there are left a number of sources of random error, some of which may be tackled, others which have to be endured. These include some effects which are global such as human error, the effects of wetting and the effects of mounting, other effects are particular to the problems encountered at Wraysbury such as the variability of weather, ambient noise and even fish! These factors are monitored by the operators and if are found to be causing a problem can in general be catered for by slight changes to operating procedures.

Of all of these factors, perhaps wetting is the hardest to quantify and cater for. Depending on transducer design, materials used etc., different transducers will require different lengths of time to stabilise after immersion in water. In some cases days may be needed to achieve absolute stability! Since it is not always practical to determine the effects of these variations, results are presented as being valid under the stated conditions of temperature, wetting and depth. For jobs which require extended periods of wetting, customers may either specify the wetting time required or measurements of wetting performance versus time. Since these variations are in general unquantifiable as an uncertainty associated with the measurement they are left as stated conditions. Similarly differences in mounting arrangements can cause subtle effects which are not easily accounted for in measurement uncertainties and hence these too are specifically recorded.

Being a free field site, the ambient noise level can be affected by many factors such as passing aircraft and prevailing weather conditions, but in general the level is so low in relation to signal levels that the effect is negligible. As mentioned in Section 2.4, during a calibration, five measurements are made at each frequency. As well as producing an average sensitivity figure, these five measurements are also used to calculate a random uncertainty contribution to the overall measurement uncertainty. This means that any signal fluctuation within the user set limit will be catered for in the uncertainty calculation.
A further hazard of an open water site can be the presence of fish, which are generally encountered only for a few weeks in summer. The fluctuation in signal level caused by the presence of fish is generally so great (up to 60dB) as to exceed the user set fluctuation limit and bring a halt to the calibration, rather than affect measurements. Any small fish induced fluctuation is catered for in the uncertainty calculation.

4. STANDARDS AND NATIONAL STANDARD TRACEABILITY

Traceability to a National Standard builds in a level of confidence to the measurements undertaken. With such traceability, all of the procedures are seen to meet a certain level of accuracy and thus confidence in the results is inspired. At the laboratory, this is achieved by annually calibrating a Reson TC4014 hydrophone and comparing this to the results of a similar calibration by the National Physical Laboratory. In order to ensure as much as possible that all measurements produced by the facility fall within the uncertainties specified and that they are indeed repeatable, this reference hydrophone is calibrated at least three times a year and on each occasion by a different member of staff, using a different station and different equipment. This route assesses the overall performance of the site; additionally all of the electronic test instruments are given an annual NAMAS calibration by Hewlett Packard, as well as being subject to regular audits by UKAS.

5. DISCUSSION

The procedures outlined above illustrate what we consider the necessary requirements of an Underwater Acoustic Calibration Service, which enable production, development and research calibrations to take place in an environment which produces the information required together with a figure of uncertainty that accurately represents the accuracy of the measurement process.

The Wraysbury calibration centre has a history going back 30 years Over this period, one of the most significant enhancements to the calibration process has been the advent of computer software to both control and analyse measurements. Whilst theoretically, a calibration should be able to be produced manually to the same degree of quality, the computer affords the chance to both remove many of the laborious tasks of calibration, together with giving improved algorithms for analysing data, producing values and also assessing the degree of uncertainty associated with a measurement. This has both decreased the operational uncertainties and by reducing opportunities for operator error, has helped ensure that measurements repeated over time regularly show little deviation.

Whilst a measurement and an accuracy alone fully calibrate a transducer under given conditions, we feel that long term repeatability of these measurements is an essential key to proving the quality of the measurements from a given site. Results taken must be able to repeat under similar conditions to within the stated accuracy, otherwise the stated accuracies are meaningless. Whilst a repetition calibration using the same equipment, carried out by the same person on the same day using the same equipment would normally be expected to repeat identically, this result has limited meaning. What is more valuable is when factors not affecting the inherent performance of the transducer are changed dramatically and results can be shown to repeat. This gives a great deal of weight to the accuracy of the calibrations and lends credence to the quality procedures installed. The results from Section 2 demonstrate both the difficulties associated with this endeavour and the degree of accuracy achievable by years of practise.

6. CONCLUSION

We have discussed the operating procedures behind a NAMAS accredited acoustic calibration facility. Such accreditation allows customers to place confidence in performed calibrations and removes the need for detailed descriptions of the employed procedures, equipment and associated uncertainties. However, even with this accreditation it is certainly of interest to the community to discuss our procedures and demonstrate what we feel is an accurate and repeatable calibration. The results shown certainly demonstrate that calibrations can be repeated (under similar conditions) with varying equipment and personnel and achieve an exceedingly good comparison over months and even years.

7. ACKNOWLEDGEMENTS

This paper is dedicated to the memory of Michael Beck.

8. REFERENCES

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