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CALIBRATION OF AN ACOUSTIC ECHO-INTEGRATION SYSTEM IN A DEEP TANK, WITH SYSTEM GAIN COMPARISONS OVER STANDARD SPHERE MATERIAL, WATER TEMPERATURE AND TIME

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Abstract

This paper outlines the theory and procedures for calibrating an echo integration acoustic system with a standard sphere. It presents the results of an extensive calibration of a Simrad EK500 scientific echosounder with a 120 kHz split-beam transducer in a refrigerated 10 m deep tank. Calibration parameters are studied in relation to sphere material (WC and Cu), water temperature (0.5 to 5.5°C), transmitted pulse length (0.1, 0.3 and 1.0 ms), target depth (0.8 to 7.5 m), and time (149 days). The total range in TS gain, including the effects of temperature, standard sphere and time, is 2.9 dB. Gain values calibrated with the Cu sphere are, with the exception of the long pulse length, lower than those from the WC sphere. The general trends are consistent between $S_{A\_}$ gain and TS gain. The total spread in $S_{A\_}$ gain, including the effects of temperature, standard sphere and time, is 2.1 dB. Thus, the accuracy of the standard sphere as a reference TS value, the pulse length, the water temperature range, and equipment instabilities during the duration of a survey can contribute significant errors to the accuracy and precision of an echo integration acoustic survey. To minimise these effects, the TS gain and $S_{A\_}$ gain parameters should be meticulously measured, measured frequently, and matched to the pulse length used and the water temperature in the survey area.

Résumé

L'auteur expose la théorie et les procédures d'étalonnage d'un système d'écho-intégration acoustique avec une sphère standard. Il présente les résultats de l'étalonnage extensif d'un échosondeur scientifique Simrad EK500 équipé d'un transducteur à faisceau fractionné de 120 kHz dans un réservoir réfrigéré de 10 m de profondeur. Les paramètres d'étalonnage sont étudiés en fonction du matériau de la sphère (WC et Cu), de la température de l'eau (de 0,5 à 5,5°C), de la durée de la pulsation transmise (0,1, 0,3 et 1,0 ms), de la profondeur de la cible (de 0,8 à 7,5 m) et de la durée (149 jours). L'intervalle total du gain TS, tenant compte des effets de la température, de la sphère standard et de la durée est de 2,9 dB. Les valeurs du gain calibrées avec la sphère de Cu sont, sauf dans le cas de la durée de la pulsation, inférieures à celles de la sphère de WC. Les tendances générales sont régulières entre les gains de $S_{A\_}$ et TS. L'étendue totale du gain de $S_{A\_}$, y compris les effets de la température, la sphère standard et la durée, est de 2,1 dB. Ainsi, la précision de la sphère standard en tant que valeur de référence de réponse acoustique, la durée de la pulsation, l'intervalle de températures de l'eau et l'instabilité de l'équipement tout au long d'une campagne peuvent contribuer à former des erreurs significatives en matière de

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justesse et de précision d'une campagne acoustique par échosondages. Pour réduire ces effets au minimum, les paramètres des gains de TS et de $S_{A\_}$ devraient être mesurés méticuleusement et fréquemment et ajustés à la durée de la pulsation utilisée et à la température de l'eau dans la zone concernée.

Резюме

Настоящая работа описывает теорию и процедуру калибровки акустической системы эхо-интеграции с помощью стандартного шара. Представлены результаты всесторонней калибровки научного эхолота типа Симрад EK 500 с помощью преобразователя с расщепленным лучом в охлаждаемом садке глубиной 10 м. Параметры калибровки изучаются по отношению к материалу шара, (вольфрамовый карбид - WC; и медь - Cu), температуре воды (0,5-5,5°C), продолжительности передаваемого пульса (0,1, 0,3 и 1,0 мс), глубине нахождения цели (0,8-7,5 м) и времени (149 дней). Общий диапазон TS-усиления, включая влияния температуры, стандартного шара и времени, составляет 2,9 дБ. Величины усиления, калиброванные с помощью шара из Cu, за исключением длительного по продолжительности импульса, ниже чем в случае шара из WC. Общие тенденции между $S_{A\_}$ и TS-усилением были последовательными. Общий диапазон $S_{A\_}$-усиления, включая влияния температуры, стандартного шара и времени, составляет 2,1 дБ. Таким образом точность стандартного шара как контрольное значение TS, продолжительность пульса, диапазон температуры воды и неустойчивость приборов во время съемки могут привести к допущению значительных ошибок в точности акустической съемки с использованием эхо-интеграции. В целях сведения к минимуму таких последствий следует тщательно и часто измерять параметры TS и $S_{A\_}$-усиления и делать поправку на используемую продолжительночть импульса и температуру воды в районе съемки.

Resumen

En el presente trabajo se describen la teoría y la práctica de la calibración de un sistema de ecointegración acústica con una esfera estándar. Se explica la calibración de un ecosondas Simrad EK500 con un transductor de haz doble a 120 kHz, en un tanque refrigerado de 10 m de profundidad. Se han estudiado los parámetros de calibración respecto del material de la esfera (WC y Cu), temperatura del agua (0.5 a 5.5°C), duración del impulso transmitido (0.1, 0.3 y 1.0 ms), profundidad del blanco (0.8 a 7.5 m), y tiempo (149 días). El valor total de TS gain, que comprende el efecto de la temperatura, la esfera estándar y el tiempo, es 2.9 dB. Los valores de ganancia calibrados con la esfera de Cu son menores que con la esfera WC, exceptuando el impulso más largo. Los valores de $S_{A\_}$ gain y TS gain son coherentes. La amplitud total de $S_{A\_}$ gain, incluyendo el efecto de la temperatura, esfera estándar y tiempo, es 2.1 dB. Por consiguiente, la precisión de la esfera estándar como valor de referencia de TS, duración del impulso, gama de temperatura del agua, y la variabilidad instrumental durante la realización del estudio pueden ocasionar errores importantes en la prospección acústica ecointegrada. Para reducir este efecto, los parámetros de TS gain y de S_A gain deberán medirse con cuidado y frecuencia, ajustándolos a la duración del impulso y a la temperatura del agua de la zona.

1. INTRODUCTION

Successful management of fisheries invariably requires accurate information about fish size, distribution and abundance. To acquire this information over large survey areas, echo integrating instruments are commonly used. Hydroacoustic instruments are attractive to researchers due to cost, survey speed and apparent ease of data analysis. However, a practical application of echo integration theory requires a meticulous and cautious interpretation of the data with respect to the many theoretical assumptions. The main contributions of bias in an echo integration acoustic survey are due to errors in calibration and target strength measurements (Tesler, 1989). Therefore, if a quantitative hydroacoustic study is to produce results of adequate accuracy, a highly accurate calibration is necessary.

Outlined first is a currently accepted methodology for calibrating a hydroacoustic system with a standard sphere (Johannesson and Mitson, 1983). The theory and procedures have been adapted to the Simrad EK500 scientific echosounder, a commonly used instrument in fish stock assessment. Both the electrical and acoustic parameters pertinent to the calibration are defined. Then, the results of an extensive calibration experiment, performed in a deep tank, are presented. Possibilities for improving the calibration equipment and procedures are suggested. Finally, the ramifications of the results on the accuracy of a hydroacoustic study are discussed.

2. CALIBRATION

Calibration is the process of standardising a measuring instrument. Typically it is performed by determining the deviation from a standard so as to ascertain the proper correction factors. In the context of hydroacoustic instruments, a popular method of calibration is to insonify a standard target on the beam axis and at a prescribed depth, calculate the difference between the standard and the measured target strength (TS), and adjust the system gain parameters to compensate for the discrepancy. Spherical standards are commonly used for fisheries calibration because the TS remains stable, they are independent of orientation, and no additional electronic equipment is required (Blue, 1984). Furthermore, the method is repeatable, thus allowing performance changes for the entire system to be monitored over time.

In order to realise the potential accuracy of the standard target technique, considerable care must be taken to position the target on the acoustic axis of the survey transducer (Robinson, 1984). Then, unless the beam pattern is known, the resulting calibration refers only to the axis. Knowledge of the transducer beam pattern permits relative gain compensation algorithms to be effected off axis. Calibration should be performed under the complete range of operating conditions and equipment settings. It should be performed with no effect from the water column boundaries so that only spherical waves reflecting from the target return to the transducer. The water should be homogeneous and isotropic. The water temperature and salinity should be measured to correct for absorption losses. The standard target must be held stable, but spatially adjustable, in the acoustic far-field.

$$\text{far-field} > \frac{2L^2}{\lambda}$$

where L is the longest dimension of the transducer face and λ is the wavelength of the transmitted pulse. The factor of two is commonly included in quantitative acoustics to be certain of far-field operation. Finally, the ambient noise level must be low.

Standard targets are solid elastic spheres typically made from tungsten carbide or high purity copper. The sphere diameter is selected to provide a desired target strength and to minimise the temperature dependence on TS. Operating at 120 kHz, the optimal sphere diameter for commercial, high purity copper was suggested by a preliminary investigation to be 30.05 mm (Foote, 1981). Improved knowledge of the elastic properties has recently enabled better sphere designs (Foote, personal correspondence). Electrical grade copper (Cu) resists corrosion in sea water and is inexpensive and machineable (Foote, 1984a and b). Tungsten carbide (WC) is extremely hard and therefore has highly elastic acoustic characteristics. Due to its extreme hardness, it is sintered into a spherical shape rather than machined. Consequently, the diameters of WC spheres are commonly more precise than those of Cu spheres.

To suspend and move the sphere in the beam, a typical set-up includes multiple monofilament lines connected to the sphere and manipulated using fishing reels, stepping motors, or similar apparatus. Attaching the lines to the sphere without affecting its acoustic properties is difficult, but a fine mesh nylon bag or monofilament net is commonly used. Before deploying, the surface of the sphere should be cleaned and deaerated in a solution of soap and fresh water.

Calibration data is normally supplied with a new transducer. This data usually includes the leakage resistance, beam pattern, beam width, impedance, directivity index, transmitting response, receiving sensitivity, and electro-acoustic efficiency. The manufacturer may test the transducer in a configuration completely different than that used in the actual deployment. It may be tested with a different transmission cable length, mounting configuration, water temperature and salinity, transmitted power, and/or pulse length. The electrical and material properties of the transducer are susceptible to changes over temperature and time.

Ideally, all of the calibration parameters should be re-checked under the actual operating configuration, over the entire range of anticipated survey settings and conditions, and as often as possible. In usual practice, however, only the leakage resistance, beam axis and beam width are tested explicitly while the remaining factors are either accepted from the manufacturer's specifications (beam pattern, effective beam width and directivity index), or lumped into the system gain settings (impedance, transmitting response, receiving sensitivity, and electro-acoustic efficiency).

Leakage resistance refers to the sum of electrical resistances between the hull of the ship and the transducer cable screen and between the individual transducer leads and the cable screen. These resistances should be measured with the deck and/or towing cable(s) attached to the transducer. Leakage resistance values should be many MΩ. A low leakage resistance may cause excessive noise due to ground loops. The resistance of the transducer (single-beam), or each transducer section (dual- or split-beam), should also be checked between each pair of transducer leads. Transducer resistances should be measured at all accessible points along the connecting cable (i.e., pig-tail, winch slip-rings, back of echosounder, etc.). If repeated frequently, these measurements will warn of connectivity problems - a concern particularly in towed systems.

To measure the beam width, TS data should be collected from the on-axis signal level of the main lobe to a level less than 6 dB down in both alongship and athwartship directions (Simmonds, 1984a and b). A two-dimensional polynomial is fit to these data to approximate the angle between half power points and to determine the offset angles of the beam axis. Another method of estimating beam angles and offsets is to fit a surface of TS data points to a modified Bessel function (Ona, 1990).

The impedance, transmitter response, receiving sensitivity, and electro-acoustic efficiency are typically measured collectively while calibrating with a standard sphere to adjust the overall system gain. The EK500 processes the signal digitally immediately following the receiver front end. Therefore, changes in gain are effected by altering software parameters (TS gain and volume scattering strength gain, S*v* gain), rather than an analog gain.

To be thorough, the transducer impedance, transmitter frequency, pulse length, pulse repetition rate, and transmitted power can also be tested. The impedance of the transducer should be measured in the survey configuration (i.e., all connecting cables, slip-rings, etc. attached). Transducers made of piezoelectric ceramic materials are capacitive, and the impedance has one maximum at the nominal resonance frequency. Ideally they are tuned at this frequency, using a coil and transformer, to be purely resistive. Practically, however, the complex impedance of the cable plus transducer will exhibit some phase difference between the voltage and the current. Although the impedence of transducers is usually tuned in the factory to be 60 Ω at the nominal operating frequency, the true impedance with the cable attached may be significantly different.

As electronic settings drift over time, the transmitter operating frequency, pulse length (PL), and pulse repetition rate (PRR) may also move outside the specified limits. However, Foote (1981) measured the effect of modulating the centre frequency and the transmit pulse duration by ±1% and ±0.5 ms to total less than ±0.05 dB on the TS of one sphere.

3. EQUIPMENT AND PROCEDURES

An extensive calibration was performed on a Simrad EK500 echosounder with a 120 kHz split-beam transducer in a deep tank facility at Scripps Institution of Oceanography (Figure 1). Calibration parameters were studied in relation to sphere material (WC and Cu), water temperature (0.5 to 5.5°C), transmitted pulse length (0.1, 0.3, and 1.0 ms), target depth (0.8 to 7.5 m), and time (pre- and post-cruise). The calibration was in preparation for an acoustic survey of Antarctic krill (*Euphausia superba*) in a study area around Elephant Island.

The deep tank is a cylindrical steel structure, approximately 10 m deep by 3 m in diameter. It was filled with ocean water pumped from the end of Scripp's pier. A pump and refrigeration unit allowed the water inside the tank to be chilled from ambient ocean temperature (~15°C) to 0.5°C. A second pump was used to vertically circulate the tank water, keeping it well mixed so that temperature strata would not develop. The outside of the tank is fully insulated and fitted with multiple observation ports. Before each set of measurements, a calibrated thermistor (YSI 44008 30K) was used to profile the tank temperature at 1 m depth intervals from the surface to 10 m. Uniform temperature profiles (target temperature (T_t) ±0.2°C) were achieved over most of the tank (2 to 10 m). The temperature of the surface water (0 to 2 m) varied from the T_t±0.2 to T_t±1°C depending on the time of day.

The main components of the acoustic system included a Simrad echo integration system (EK500), a UNIX work station for postprocessing (Sun Sparc Station 1+), and a Simrad 120 kHz split-beam transducer (ES120). The transducer was tethered radially with three nylon cords in the centre of the tank at a depth of 0.5 m. It was connected to the EK500 through a 50 m towing cable, a 13-conductor slip-ring set, and a 75 m deck cable.

The acoustic characteristics of a 33.17 mm (specified as ~33 mm) WC sphere from Biosonics and a 30.05 mm (specified as 30.05 mm) Cu sphere from Simrad were compared versus temperature, pulse length, and time. In successive trials, each sphere was suspended and controlled by three monofilament lines connected to three fishing reels. The lines were attached to the WC sphere by a monofilament knotted bag and to the Cu sphere by a loop of monofilament nylon affixed into a single shallow bore. The effect of the bore is still undetermined in the case of the 120 kHz echosounder (Foote, 1981).

The nominal equipment and environmental parameters were:

Transducer model:	Simrad ES120 (split-beam)
Frequency (kHz):	119.047 (centre)
Pulse Length (ms):	0.1 short, 0.3 med, 1.0 long
Pulse Rep. Freq. (Hz):	1
Bandwidth (kHz):	12.0 (Wide), 1.2 (Narrow)
Transmit power (kW):	1 (Normal)
Angle Sens. (deg.):	17.0
2-Way Beam Angle (deg.):	-18.5
3-dB Beamwidth (deg.):	9.0
Sample Distance (cm):	3
Sampling Freq. (kHz):	50
Nom. Water Temp. (°C):	5.5, 5.0, 3.5, 3.0, 1.0, 0.5
Salinity (‰):	34.0 (±0.5)

A wide receiver bandwidth was used with the short and medium pulse lengths and a narrow bandwidth was used with the long pulse length. For all three pulse lengths, the noise margin was 0 dB, the depth range was 10 m, and the time varied gain (TVG) was set to 40log(*r*).

Temporal variations were evaluated by repeating parts of the experiment pre- and post-cruise. The pre-cruise calibration experiments were conducted from 16 to 19 November 1991, and the post-season experiments were performed from 17 to 18 April 1992, a 149 day separation.

4. DATA ANALYSIS

To determine the centre of the main lobe and to estimate the effective beamwidth, pre-cruise TS measurements were recorded from the WC sphere at 5±1 m depth, over ±6.0° alongship and athwartship angles, and at 0.5° C (Figure 2). By maintaining near zero offset (±1°) in one of the two directions, the alongship and athwartship data were independently fitted, in the least squares sense, with second-order polynomials.

$$TS_{\text{alongship}} = 0.40\Theta^2_{\text{alongship}} - 0.11\Theta_{\text{alongship}} - 44.23$$

$$TS_{\text{athwartship}} = 0.38\Theta^2_{\text{athwartship}} - 0.01\Theta_{\text{athwartship}} - 44.27$$

The maximum value of these equations provides a good estimate of the beam axis location. Therefore, the beam is centred at -0.1° alongship and 0.0° athwartship angles. The echosounder was adjusted for this slight offset. Since a target was measured, rather than a microphone, the total gain is a product of the transducer's transmit and receive gains. Therefore, solving the equations for the -6 dB points indicates a beam widths of 7.8° and 7.9° alongship and athwartship, respectively. The vendor specified beamwidth at half-power points for this transducer is a symmetrical 9.4°. However, since the measurements of angle are made by the same sounder as is calibrated, the actual beam width and the measured beamwidth may differ. In fact, the angle sensitivity parameter, or the conversion factor between electrical and mechanical angles, will change the measured beam width.

The theoretical near-field / far-field transition distance is approximately 1.02 m from the transducer ($\lambda \cong 1.25$ cm, $L \cong 8$ cm). Pre-cruise TS measurements taken from the WC sphere at 0.5°C and distances of 0.8 to 7.5 m confirmed that transition occurs at a distance of approximately 1.1 m (Figure 3). Beyond the transition range, however, the maximum target strength values taken on-axis had a large range of 1.1 dB (-43.9 to -42.8 dB). It is unclear whether this spread is inherent in the system and target or if the Deep Tank boundaries are causing significant reverberation from the side-lobes. Range uncertainty, due to the 3 cm sampling distance, may also be suspect. To minimise the effect of this variation, a constant target depth of 5 m was chosen for the remainder of the measurements.

The target strength measurement (TS) is based upon the maximum sample value of the standard sphere echo:

$$\text{TS gain}_{\text{new}} = \text{TS gain}_{\text{old}} + \frac{\text{TS}_{\text{measured}} - \text{TS}_{\text{sphere}}}{2}$$

TS gain$_{\text{old}}$ was held at a constant reference value of 23.0 dB throughout all of the testing. The TS$_{\text{sphere}}$ values are from the vendor supplied data sheets at the appropriate sound velocity. Biosonics claims the TS accuracy to be within ±0.2 dB for pulse lengths of 0.5 ms or more. Simrad's data sheet (TS versus sound velocity) included no claim about accuracy. The sound velocity was calculated at each temperature and at a depth of 5 m and a salinity of 34‰ (Mackenzie, 1981). TS$_{\text{comp}}$ values are the maximum sample values of the echo from the sphere, taken on-axis (Table 1 and Figure 4). On-axis stability decreased with increasing pulse length. Therefore, if no data were collected exactly on axis, the nearest data to the axis were used after being multiplied by a beam pattern compensation factor.

There is a possible trend of increasing TS gain values with increasing pulse length (PL). This trend is consistent between the short and medium PL gains. However, with the small number of data points and the possible range of TS$_{\text{sphere}}$ values (0.4 dB) , this cannot be stated with any certainty. The gain values associated with the long PL have the greatest variance. TS gain exhibits a flat, if not slightly increasing trend over the 5°C temperature range. This is consistent with the observation by Foote (1984a and b) who reported the TS of a tungsten carbide and a copper sphere to vary by ±0.2 dB and ±0.1 dB from 0 to 30°C, respectively. TS gain values were higher for short PL than for medium PL. The total spread in TS gain, including the effects of temperature, standard sphere and time, is 2.9 dB.

Gain values calibrated with the Cu sphere are, with the exception of the long PL, lower than those from the WC sphere. Since the WC sphere diameter was slightly larger than specified, the true TS$_{\text{sphere}}$ may be different from that reported by Biosonics. Foote (1984) calculated the effect of a ±0.1 mm variation in sphere diameter to be ±0.02 dB on TS. This corresponds to an increase of TS$_{\text{sphere}}$ by approximately 0.04 dB.

The integrated backscattering area (S_A) is based upon integrated and averaged echo samples. The theoretical value, used as a calibration reference, is:

$$S_{A_{\text{theory}}} = \frac{4\pi r_0 \sigma_{bs} (1852\text{m} / \text{nm})^2}{\Psi r^2}$$

where r_0 is the standard reference distance for backscattering (1 m), σ_{bs} is the backscattering cross-section of the sphere, Ψ is the equivalent two-way beam angle, and r is the target range. The calibrated integration gain is:

$$S_{A\_}\ \text{gain}_{\text{new}} = S_{A\_}\ \text{gain}_{\text{old}} + \frac{10\log\left(S_{A_{\text{measured}}} / S_{A_{\text{theory}}}\right)}{2}$$

$S_{A_{\text{measured}}}$ is the average of three or more measurements taken while the target sphere was stable on the beam axis (±0.2 for short, ±0.4° for medium, and ±1.0 degree for long PL).

The general trends are consistent between $S_{A\_}$ gain and TS gain (Table 2 and Figure 5). Again, the gain values for the medium PL are consistently higher than those for the short PL, those associated with the long PL have the greatest variance, and the values for the Cu sphere are generally lower than those from the WC sphere. The total spread in $S_{A\_}$ gain, including the effects of temperature, standard sphere and time, is 2.1 dB, i.e., 0.8 dB less than the total range of TS gain.

Resistances (Ω) of the deck-cable, slip-rings, tow-cable, and transducer quadrant were:

Quadrant:	1	2	3	4
Pre-cruise:	8.5	8.4	8.4	8.4
Post-cruise:	8.9	8.8	8.9	8.9

All leakage resistance values were greater than 32 MΩ both pre- and post-cruise.

Summarising, the ranges of both the TS gain and the $S_{A\_}$ gain have been tabulated versus temperature (5.5 to 0.5°C), time (~149 days), and sphere material (WC, Cu) for each of the three pulse lengths (Table 3). Over the 5°C temperature spread, the ranges of TS gain and $S_{A\_}$ gain were greatest for the long PL (1.2 and 1.1 dB, respectively). This may be due to second echo interference or reverberation from the tank walls. Both TS gain and $S_{A\_}$ gain were consistently higher for short PL than for medium PL. Temporal drift of the system calibration ranged from -0.1 to -1.3 dB for TS gain and -0.2 to -1.2 dB for $S_{A\_}$ gain, including the effects of PL and standard sphere. In general, the drift in gain increased with increasing pulse length and all of the changes were negative. The increase in resistance for each quadrant is consistent with the latter observation. TS gain and $S_{A\_}$ gain differed between spheres by as much as 1.5 and 1.0 dB, respectively.

5. DISCUSSION

Foote *et al.* (1984a and b) stated that precision calibrations to within 0.5 dB are possible by means of standard calibration spheres. Assuming an accuracy of 0.5 dB for calibration with a standard target, the error of estimating mean target strength will be 1 dB (Tesler, 1989). Robinson and Hood (1984) asserted that if the specifications of the best currently available equipments are used, and assuming that the equivalent beamwidth can be measured to ±0.1 dB, it is currently only possible to state that an acoustic system can be calibrated to within ±0.6 dB (95% confidence). He stated that the acoustic absorption coefficient is not known to better than ±5 dB/km at 120 kHz. Thus, calibration accuracies at a range of 50 m, influenced by this parameter alone, can be no better than ±0.5 dB. At greater ranges, the biases are proportionally larger (Robinson, 1984).

The results of this experiment indicate that variations in PL, time and choice of standard sphere can cause corresponding variations in the system gain of 1.2, 1.3, and 1.5 dB, respectively, all else being equal. Therefore, while using a currently accepted procedure for calibrating, a commonly used echosounder and a short pulse length, the error in mean target strength estimates of animals in 0.5°C water could be as high as 3.0 dB. This error due only to one's choice of calibration sphere.

However, the reader should note that multiple changes in the experimental equipment and procedures may provide less troubling results. For instance, if the ES120 transducer is used, an angle sensitivity of 15.7 is a better factor to match the mechanical angles with the measured phase angles (Ona, personal correspondence). Simrad currently supplies a 23.0 mm Cu sphere with a nominal TS of -40.5 dB to calibrate at 120 kHz. This sphere exhibits a smaller TS change with temperature. If WC is to be used, Foote (personal correspondence) currently recommends a 38.1 mm diameter sphere. Also, if calibrations are performed in a tank, the sphere should be suspended just outside the near-field/far-field transition zone. A closer range than used throughout these experiments may reduce or eliminate the effects of side-lobe and second-echo reverberation from the tank boundaries.

6. CONCLUSIONS

Calibration of an echo integration system for use in biomass estimation is critical for understanding and quantifying the accuracy and precision of the resulting measurements. The calibration must be performed with the system configuration used during the survey and over the range of equipment settings used and water temperatures encountered during the survey. The calibration should be repeated at least twice, before and after the survey. The results of the calibration should be included in the statistical analysis of the biomass estimates.

The accuracy of the standard sphere as a reference TS value, the pulse length, the water temperature range, and equipment instabilities during the duration of a survey can contribute significant errors to the calibration accuracy of an echo-integration acoustic system. To minimise the effects of these parameters on the accuracy and precision of an acoustic survey, the TS gain and S_{A} gain parameters should be meticulously measured, measured frequently, and matched to the pulse length used and the water temperature in the survey area. Furthermore, additional comparative studies should be performed to understand the practical, opposed to theoretical, accuracies and precisions of the two most commonly used calibration sphere materials (WC and Cu). Particular attention should be paid to variations in calibrated gains versus water temperature.

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Table 1: Calibration data for TS gain.

Date	Sphere Mat.	Pulse Length (ms)	Temp. (c)	TScomp (dB)	Depth (m)	Along (deg.)	Athwart (deg.)	Sound Speed (m/s)	TS sphere (dB)	TS gain (dB)
11/16/91	WC	0.1	5.5	-42.5	5.1	0.0	0.0	1514	-40.7	22.1
11/16/91	WC	0.3	5.5	-42.9	5.1	0.0	0.0	1514	-40.7	21.9
11/16/91	WC	1.0	5.5	-41.2	5.2	0.0	1.5	1514	-40.7	22.8
11/16/91	WC	0.1	5.0	-42.7	5.1	0.0	0.0	1512	-40.7	22.0
11/16/91	WC	0.3	5.0	-43.2	5.1	0.0	0.0	1512	-40.7	21.8
11/16/91	WC	1.0	5.0	-41.7	5.2	-0.2	0.0	1512	-40.7	22.5
11/17/91	WC	0.1	3.0	-42.6	5.2	0.0	0.0	1503	-40.6	22.0
11/17/91	WC	0.3	3.0	-43.1	5.2	0.0	0.0	1503	-40.6	21.8
11/17/91	WC	1.0	3.0	-41.2	5.3	0.0	0.0	1503	-40.6	22.7
11/17/91	WC	0.1	2.5	-42.6	5.2	0.0	0.0	1501	-40.6	22.0
11/17/91	WC	0.3	2.5	-43.2	5.2	0.0	0.0	1501	-40.6	21.7
11/17/91	WC	1.0	2.5	-43.4	5.3	-0.7	0.3	1501	-40.6	21.6
11/18/91	WC	0.1	1.0	-42.9	5.2	0.0	0.0	1495	-40.6	21.9
11/18/91	WC	0.3	1.0	-43.0	5.2	0.0	0.0	1495	-40.6	21.8
11/18/91	WC	1.0	1.0	-43.0	5.3	0.0	-0.2	1495	-40.6	21.8
11/19/91	WC	0.1	0.5	-43.4	5.1	0.0	0.0	1492	-40.6	21.6
11/19/91	WC	0.3	0.5	-43.6	5.1	0.0	0.0	1492	-40.6	21.5
11/19/91	WC	1.0	0.5	-42.5	5.3	0.0	0.0	1492	-40.6	22.1
04/18/92	WC	0.1	0.5	-43.7	5.1	0.0	0.0	1492	-40.6	21.5
04/18/92	WC	0.3	0.5	-43.9	5.1	0.0	0.0	1492	-40.6	21.4
04/18/92	WC	1.0	0.5	-43.1	5.2	0.0	0.5	1492	-40.6	21.8
11/19/91	Cu	0.1	0.5	-41.4	5.1	0.0	0.0	1492	-36.2	20.4
11/19/91	Cu	0.3	0.5	-40.2	5.1	0.0	0.0	1492	-36.2	21.0
11/19/91	Cu	1.0	0.5	-38.2	5.2	0.0	0.0	1492	-36.2	22.0
04/18/92	Cu	0.1	0.5	-42.3	5.0	0.0	0.0	1492	-36.2	20.0
04/18/92	Cu	0.3	0.5	-42.4	5.0	0.0	0.0	1492	-36.2	19.9
04/18/92	Cu	1.0	0.5	-40.9	5.1	0.7	-0.3	1492	-36.2	20.7

Table 2: Data used to calculate calibrated $S_{A\_}$ gain.

Date	Sphere	Pulse Length (ms)	Temp. (c)	Depth (m)	$S_{A\_}$ measured (m^2/nm^2)	$S_{A\_}$ theory (m^2/nm^2)	$S_{A\_}$ gain (dB)
11/16/91	WC	0.1	5.5	5.1	6155.0	9318.6	22.1
11/16/91	WC	0.3	5.5	5.1	5541.0	9318.6	21.9
11/16/91	WC	1.0	5.5	5.2	4534.0	8963.7	21.5
11/16/91	WC	0.1	5.0	5.1	5907.0	9318.6	22.0
11/16/91	WC	0.3	5.0	5.1	5346.0	9318.6	21.8
11/16/91	WC	1.0	5.0	5.2	7402.0	8963.7	22.6
11/17/91	WC	0.1	3.0	5.2	5829.0	9172.4	22.0
11/17/91	WC	0.3	3.0	5.2	5536.0	9172.4	21.9
11/17/91	WC	1.0	3.0	5.3	4436.0	8829.6	21.5
11/17/91	WC	0.1	2.5	5.2	5972.0	9172.4	22.1
11./17/91	WC	0.3	2.5	5.2	5089.0	9172.4	21.7
11/17/91	WC	1.0	2.5	5.3	5738.0	8829.6	22.1
11/18/91	WC	0.1	1.0	5.2	5779.0	9172.4	22.0
11/18/91	WC	0.3	1.0	5.2	5407.0	9172.4	21.9
11/18/91	WC	1.0	1.0	5.3	6057.0	8829.6	22.2
11/19/91	WC	0.1	0.5	5.1	5359.0	9535.7	21.7
11/19/91	WC	0.3	0.5	5.1	5164.0	9535.7	21.7
11/19/91	WC	1.0	0.5	5.3	4758.0	8829.6	21.7
04/18/92	WC	0.1	0.5	5.1	4767.0	9535.7	21.5
04/18/92	WC	0.3	0.5	5.1	4627.0	9535.7	21.4
04/18/92	WC	1.0	0.5	5.2	2947.0	9172.4	20.5
11/19/91	Cu	0.1	0.5	5.1	10086.0	26263.4	20.9
11/19/91	Cu	0.3	0.5	5.1	10202.0	26263.4	20.9
11/19/91	Cu	1.0	0.5	5.2	11959.0	25263.0	21.4
04/18/92	Cu	0-.1	0.5	5.0	8709.0	27324.5	20.5
04/18/92	Cu	0.3	0.5	5.0	9039.0	27324.5	20.6
04/18/92	Cu	1.0	0.5	5.1	10417.0	26263.4	21.0

Table 3: Ranges in gain over sphere material, pulse length, water temperature, and time.

Ranges over temperature:

TS gain:

	0.1 ms	0.3 ms	1.0 ms
WC	0.5	0.4	1.2

$S_{A\_}$ gain:

	0.1 ms	0.3 ms	1.0 ms
WC	0.4	0.2	1.1

Ranges over spheres:

TS gain:

	0.1 ms	0.3 ms	1.0 ms
WC	-0.1	-0.1	-0.3
Cu	-0.4	-1.1	-1.3

$S_{A\_}$ gain:

	0.1 ms	0.3 ms	1.0 ms
WC	-0.2	-0.3	-1.2
Cu	-0.4	-0.3	-0.4

Ranges over time:

TS gain:

	0.1 ms	0.3 ms	1.0 ms
Pre	1.2	0.5	0.1
Post	1.5	0.5	1.1

$S_{A\_}$ gain:

	0.1 ms	0.3 ms	1.0 ms
Pre	0.8	0.8	0.3
Post	1.0	0.8	0.5

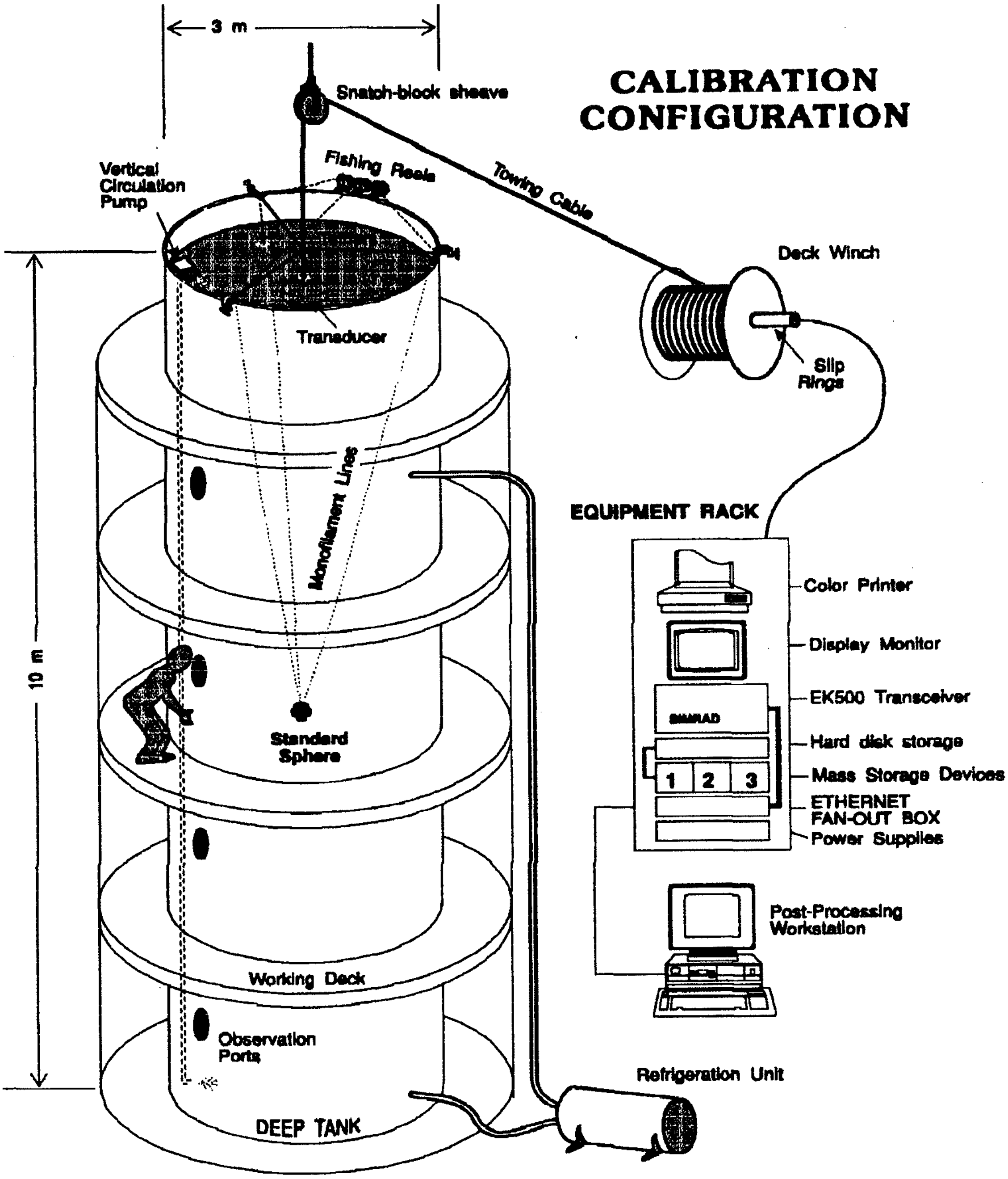

Figure 1: Calibration configuration.

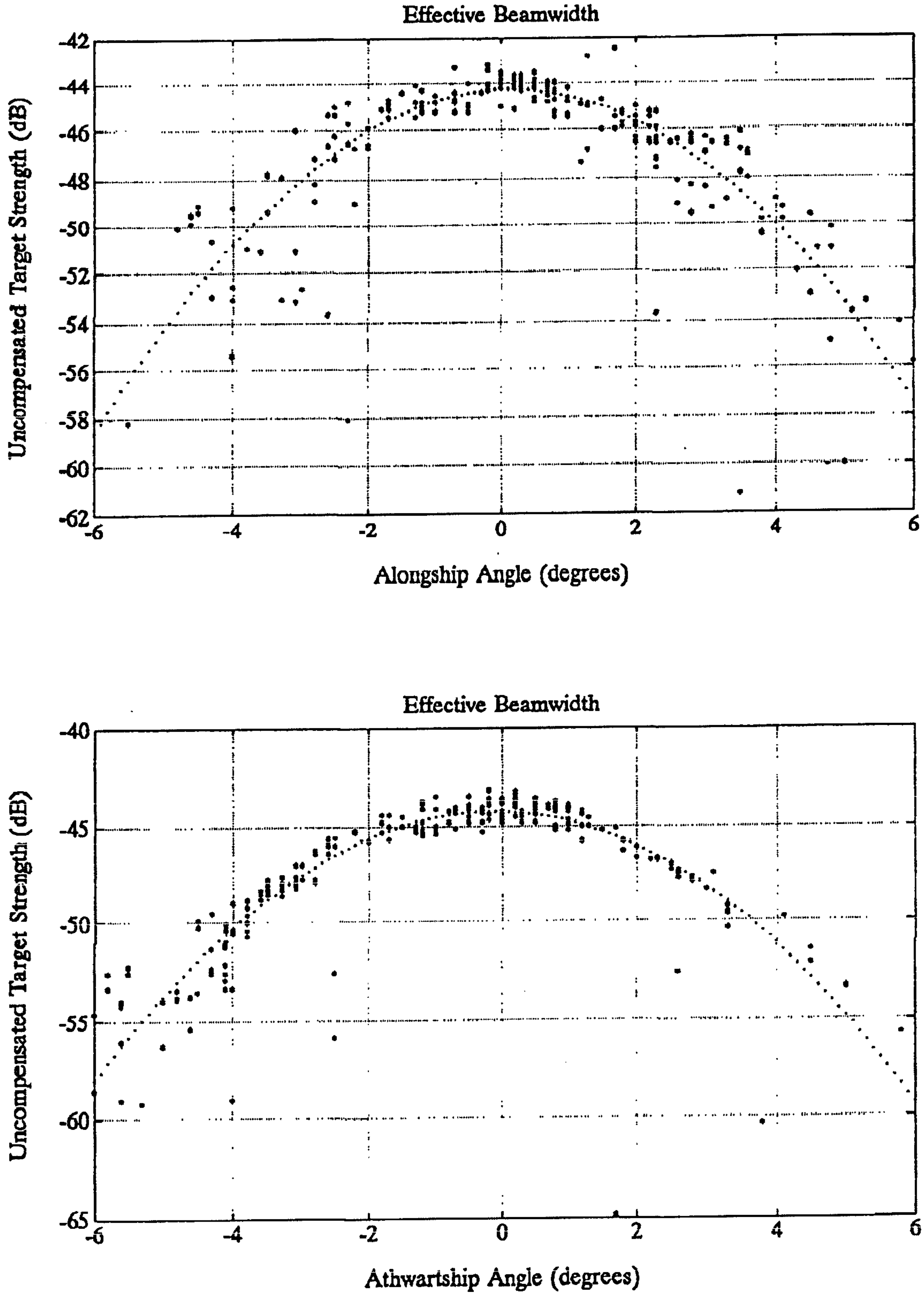

Figure 2: Beam width and offset angle determination.

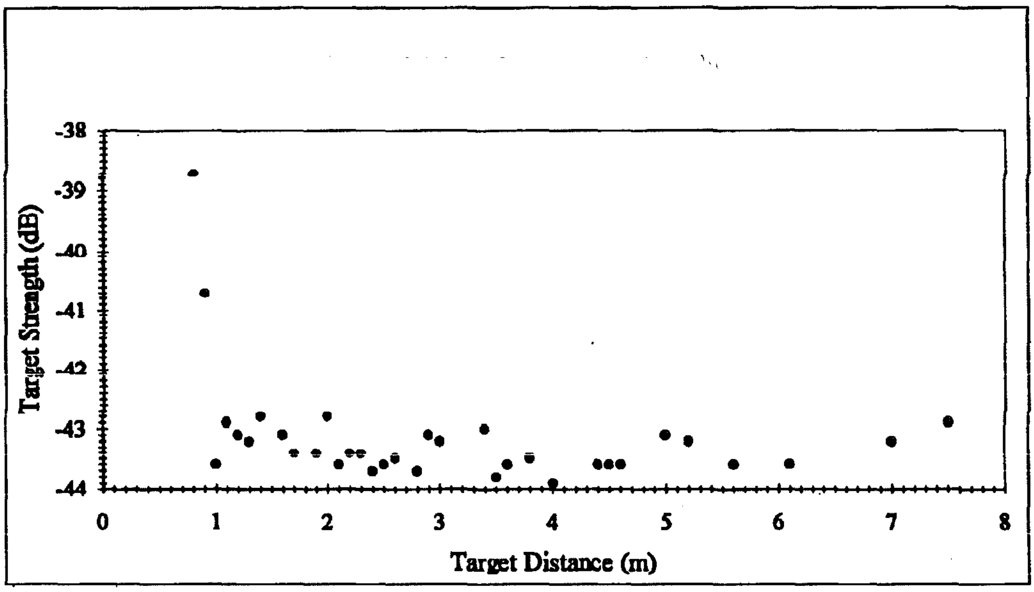

Figure 3: Near-to-far-field transition map.

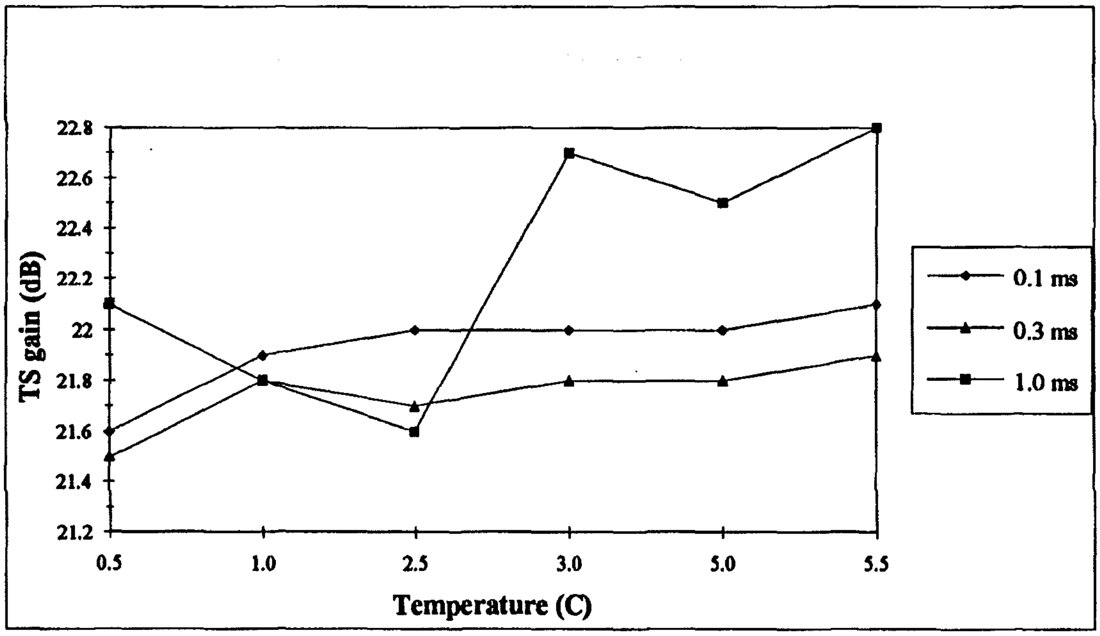

Figure 4: TS gain versus temperature.

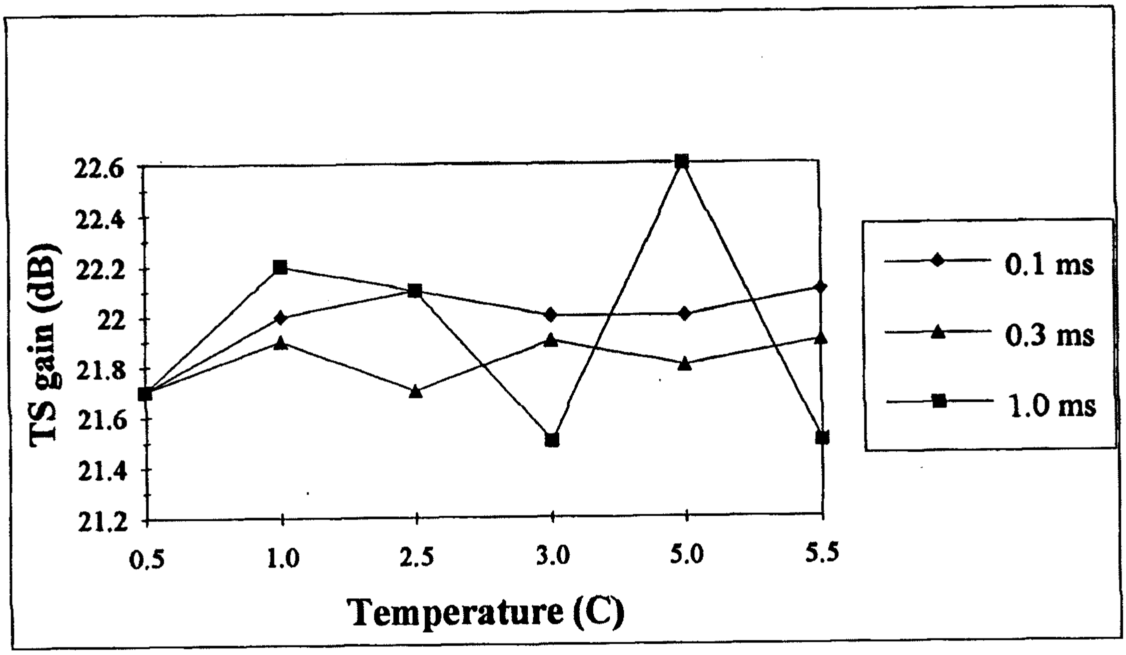

Figure 5: $s_{A\_}$ gain versus temperature.

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