OneFish Engineering, LLC
916 Pioneer Avenue
Fort Collins, CO 80521

Phone (970) 224-2721
Web www.OneFishEngineering.com
Email Craig@OneFishEngineering.com

# Acoustic Beam Calibration Procedure

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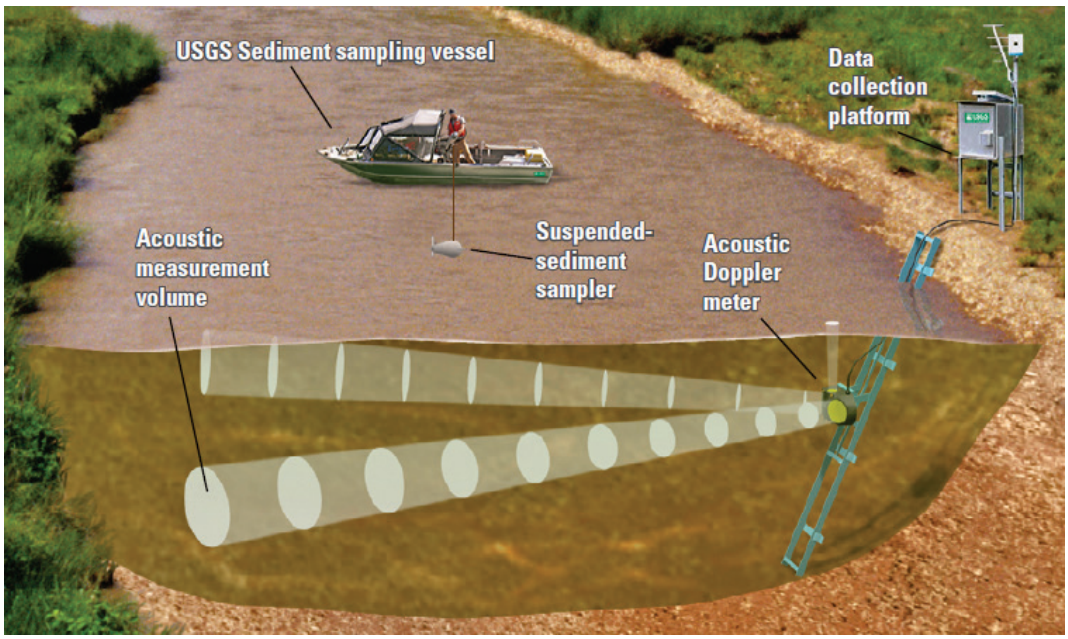


**Figure 1 - Typical Side Looking ADVM Sediment Measurement Station**

Prepared by:

Craig Huhta
OneFish Engineering, LLC
916 Pioneer Ave, Fort Collins, CO 80521
Phone (970) 224-2721
Email Craig@OneFishEngineering.com

Prepared for:

Molly Wood, P.E.
National Sediment Specialist
USGS Water Mission Area

230 Collins Road, Boise, ID 83702
Phone (208) 387-1320
Email mswood@usgs.gov

Tim Straub, P.E.
Acting Chief – Federal Interagency Sedimentation Project (FISP)
USGS Central Midwest Science Center
405 N. Goodwin Ave, Urbana, IL 61801
Phone (217) 328-9735
Email tdstraub@usgs.gov

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## Executive Summary

Acoustic Doppler velocity meters (ADVMs) can be used for monitoring of suspended sediment concentration (SSC) through the development of a site-specific sediment acoustic index rating. However, if the ADVM at a site needs to be replaced, the rating for that site may not be able to be used with the new system – even for the same make, model and frequency. Generating a new rating for the replacement instrument is an expensive and time consuming process.

As part of the Federal Interagency Sediment Project (FISP), the U.S. Geological Survey (USGS) hired OneFish Engineering, LLC (OneFish) to recommend an acoustic beam calibration procedure for ADVMs. The procedure should allow a calibrated ADVM to be replaced by another of the same make, model and frequency without re-generating the sediment acoustic rating. Ideally, the procedure would allow replacement with any calibrated system operating at the same acoustic frequency regardless of make and model.

An effective calibration technique should accomplish the following.

- It should estimate the offset in measured backscatter between different ADVMs. Potential sources of this include the transmit signal intensity and overall receiver sensitivity.
- It should estimate the linearity and slope of the measured backscatter over the dynamic range of the system. This is primarily driven by the intensity scale factor (K) of the ADVM receiver, but may also be influenced by other factors.
- Ideally the calibration would provide the following, although these are not essential.
    - Transmit and receive beam patterns
    - Near-field response
    - Offset between measured and absolute backscatter
- The procedure should have an overall accuracy similar to the resolution of ADVM measured backscatter data (0.2-0.6 dB).

OneFish reviewed the methodology applied at sediment acoustic sites, spoke with ADVM manufacturers, evaluated a number of potential calibration techniques, and searched for appropriate equipment and facilities to conduct the calibration. Based on this research, OneFish recommends the following.

- The calibration should use a reference hydrophone to measure transmit and receive characteristics. Measured backscatter could then be converted to absolute backscatter which could be compared with any instrument operating at the same frequency.
    - Calibrated hydrophones can be leased from the U.S. Navy Underwater Sound Reference Division (USRD). The cost of a lease is $3,000-$4,000 per year, and includes annual re-calibration of the hydrophone.
    - The technique could be applied to ADVMs from any manufacturer.
    - USRD hydrophones are calibrated to a maximum frequency of 2000 kHz. They may be able to provide calibration for ADVMs that operate at higher frequencies, but this would need to be confirmed during testing.
- The method requires a relatively large laboratory tank with little to no water velocity.
    - Custom mounting and data collection systems would need to be developed for the procedure. These systems would have a low to moderate level of complexity.

    - The ADVM and hydrophone would be mounted and aligned a known distance apart in the tank.
    - During the development of the procedure, detailed data would be collected for each specific make, model and frequency of ADVM.
        - This would include transmit and receive beam patterns, and the near-field response.
        - These tests would be required only once for each system type; they would not need to be repeated for individual device.
        - Initial tests and development of the procedure are estimated to require 2-3 personnel, 1-2 weeks of laboratory work, plus additional time for preparation, analysis and documentation.
    - To calibrate an individual system:
        - The ADVM would transmit and the hydrophone would receive this signal; the voltage measured by the hydrophone can be converted directly to the physical pressure of the acoustic pulse in the water.
        - The hydrophone would then transmit using a wide range of driving voltage, and the ADVM measured backscatter would be recorded. The hydrophone calibration would allow the ADVM data to be converted directly to physical pressure.
        - After analysis, the calibration would convert the recorded data from an ADVM to absolute backscatter. This data could then be directly compared to data from any other calibrated ADVM of the same frequency.
        - Calibration of a two beam ADVM is anticipated to take one person, one day of laboratory work, plus additional time for data analysis.
- The most promising facility to conduct these tests is the USGS Hydrologic Instrument Facility (HIF) in Mississippi.
    - They have existing tanks that would be suitable to the application.
    - They do not currently possess a reference hydrophone, and would need to lease one from the USRD. This is a straight forward process.
    - They have broad experience working with ADVMs, and currently employ or have access to the type of personnel that would be required.
- It would also be possible to hire USRD facilities and personnel for the calibration, if preferred.

OneFish is happy to discuss these results and all potential calibration concerns with interested parties, and to assist as needed in further development of a calibration procedure.

# Background

Suspended sediment characteristics can be computed from backscatter intensity data collected by ADVMs, providing cost-effective time series data that cannot be readily collected by other methods. This data is essential for addressing many environmental, engineering and agricultural concerns.

The measurement of suspended sediment from acoustic backscatter is a complicated process, and is dependent upon the instrument used and conditions in the field (Landers and others, 2016; Topping and Wright, 2016). Research in this area has been ongoing for many years, and standardized methods are a comparatively recent development. These techniques will likely continue to be revised and improved in the future.

The measurement of backscatter intensity is not the primary purpose of ADVMs, and the data from individual instruments is not precisely calibrated. The sediment acoustic rating developed for each site is to some degree dependent on the individual instrument installed. If this instrument needs to be replaced because of malfunction, upgrade, or some other reason, the rating may need to be regenerated – a costly and time consuming process.

## Purpose and Scope

The USGS asked OneFish to review the methodology and instrumentation used to compute suspended sediment concentration from ADVM backscatter intensity data, and to evaluate and recommend methods to calibrate this data.

- The project focused on horizontal profiling ADVMs ("side-looking" systems), although the recommended calibration would be applicable to other instruments.
- At a minimum, the calibration should allow the exchange of any ADVM of the same make, model and frequency. Ideally it would allow the exchange of any ADVM operating at the same frequency.

OneFish completed the following tasks to accomplish this goal.

- Reviewed existing ADVM sediment monitoring methodology to understand the range of instruments used, data analysis techniques, and challenges faced
- Worked with ADVM manufacturers to evaluate available instruments, variations in data provided, as well as past and anticipated future changes in instrument design
- Evaluated potential beam calibration methods including reference hydrophones, suspended sediment tanks, discrete acoustic targets, or in-situ use of reference instrumentation
- Reviewed potential calibration facilities and instrumentation

## Acoustic Suspended Sediment Methodology

This section summarizes how ADVM data is used for suspended sediment monitoring. It primarily refers to papers published by the USGS that have compiled much of the work on this subject (Landers and others, 2016; Topping and Wright, 2016). OneFish has not attempted to provide references to original source materials.

### The Sonar Equation and Sediment Acoustic Index Rating

$$SL - 2*TL + TS = RL$$

**Equation 1 - The Sonar Equation (Topping and Wright, 2016 (Equation 6))**

Equation 1, the sonar equation, represents a basic overview of acoustic backscatter data.

- All parameters are in units of decibels (dB).
- SL is the source level – the acoustic energy transmitted into the water.
  - Units are dB relative to 1 μPa at a range of 1 meter from the transducer.
  - It includes effects of the transmit ($b(\theta,\phi)$) and receive ($b'(\theta,\phi)$) beam patterns (Topping and Wright, 2016 (Equation 7)).
- 2*TL is the two-way transmission loss as sound travels from the ADVM to the measurement volume and back.
  - This is described in the references, and is not presented in detail here.
  - It includes beam spreading, water absorption ($\alpha_w$), and sediment absorption ($\alpha_s$).
  - If measurements are made within the near-field of the transducer, a correction must be applied to the data ($\psi_{NF}$).
- TS is the target strength, defined in Equation 2.

$$TS = 10\log_{10}\left(\frac{I_R}{I_{INC}}\right) = 10log_{10}(S_V) + 10log_{10}(V)$$

**Equation 2 - Target Strength (Topping and Wright, 2016, Equation 15)**

  - $I_R$ is the reflected acoustic intensity 1 m from the measurement volume.
  - $I_{INC}$ in the incident acoustic intensity at the measurement volume.
  - $S_V$ is the backscattering cross section, which is a function of the material in the measurement volume.
  - V is the volume ensonified by the transmitted signal.
- RL is the measured reverberation level, defined in Equation 3.

$$RL = 10log_{10}\left(\frac{I_{RL}}{I_{REF}}\right) = K(A - A_N) + RL_{OFFSET}$$

**Equation 3 - Reverberation Level (Topping and Wright, 2016 (Equation 20))**

  - $I_{RL}$ is the intensity of the reverberation measured by the ADVM transducer.
  - $I_{REF}$ is a reference intensity for 1 μPa at the transducer face.
  - K is the intensity scale factor that converts the ADVM units of counts to dB.
  - A is the ADVM measured backscatter intensity (in counts)
  - $A_N$ is the ADVM instrument noise level (in counts)
  - $RL_{OFFSET}$ is a constant, instrument specific parameter that shifts the ADVM measured data to absolute backscatter.

A sediment acoustic rating compares measured backscatter and/or sediment absorption ($\alpha_s$) with independent measurements of SSC. This creates an empirical relationship to estimate SSC based on ADVM data.

The data analysis must account for all parameters in the sonar equation. In existing USGS processing procedures, this is done as follows.

- The following are assumed to be constant for any individual ADVM.
  - Source level (SL)
  - Transmit ($b(\theta,\phi)$) and receive ($b'(\theta,\phi)$) beam patterns
  - Intensity scale factor (K), supplied by the manufacturer
  - Offset of measured to absolute backscatter ($RL_{OFFSET}$)
- Theoretical corrections are applied for the following.
  - Beam spreading
  - Water absorption ($\alpha_w$)
  - Near-field transducer response ($\psi_{NF}$)
- Sediment absorption ($\alpha_s$) is estimated from the profile of measured backscatter versus distance from the transducer, after the theoretical corrections listed above are applied.

To collect and process ADVM data:

- The ADVM records the profile of measured backscatter (A) and noise level ($A_N$).
  - The data may be processed two ways.
    - Using A only, assuming noise is constant
    - Using ($A - A_N$), commonly called the signal to noise ratio
  - Data is converted from counts to dB using the intensity scale factor (K).
- ADVM data is corrected for the distance at which it was measured.
  - This corrects for beam spreading, water absorption and sediment absorption.
- After processing, two values are available for each ADVM beam; both are averaged over the profiling range of the system.
  - Sediment corrected backscatter (SCB), in dB
    - This is a relative measurement, compared to an unknown reference.
  - Sediment attenuation coefficient ($\alpha_s$ or SAC), in dB/m

To create a sediment acoustic rating:

- Independent depth- and width-integrated physical samples of SSC are collected at a range of conditions in the river.
- A linear regression is performed comparing SSC with SCB and/or SAC.
  - The rating can be developed for each beam, or for the average of all beams.
  - The general form of the rating is shown below; $b_0$, $b_1$, and $b_2$ are constants determined by the linear regression.

$$\log_{10}(SSC) = b_0 + b_1 * SCB + b_2 * SAC$$

**Equation 4 - Sediment Acoustic Index Rating (SCB and SAC)**

  - At many sites, the best results use a regression between only SSC and SCB.

$$\log_{10}(SSC) = b_0 + b_1 * SCB$$

**Equation 5 - Sediment Acoustic Index Rating (SCB only)**

An example rating, including the samples used for analysis, is shown in Figure 2.

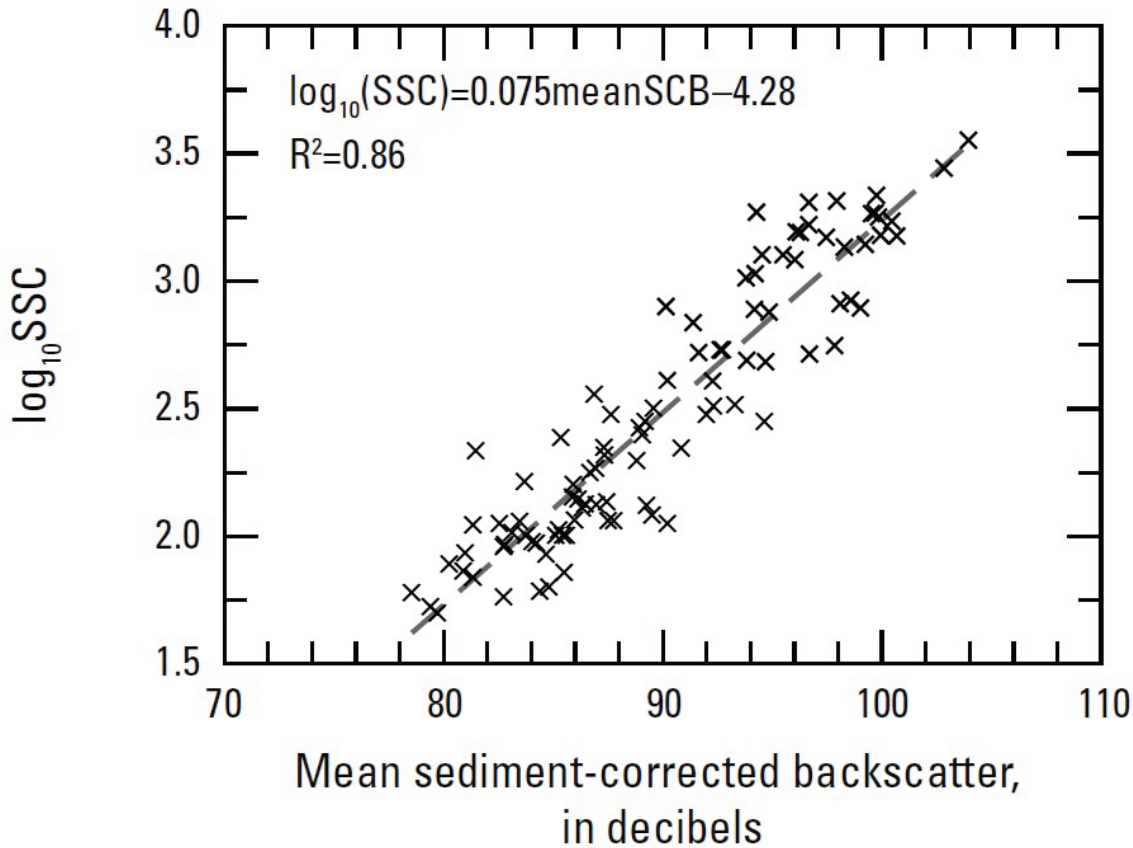


**Figure 2 - Example Acoustic Sediment Index Relation (Landers and others, 2016 (Figure 1-3))**

While there are many challenges to developing an acoustic sediment monitoring site, the technique is well developed and has been shown to be a valuable tool.

## The Problem: Instrument Specific Data

This project addresses one specific challenge to operating and maintaining an acoustic sediment monitoring site: the need to periodically replace an instrument. This might happen because of physical damage, instrument failure, instrument upgrade, or another reason.

The primary function of an ADVM is to measure water velocity; backscatter is a secondary parameter primarily intended for the QA/QC of velocity data. ADVM measured backscatter is not calibrated and can vary between instruments of the same make, model, and frequency. If an instrument at a particular site has to be replaced for any reason, the rating that has been developed for that site may not be able to be applied to the replacement instrument – even if the same make, model and frequency of instrument is used.

Figure 3 and Figure 4 show how the replacement of an instrument can affect the sediment acoustic index rating for an established site.

- In both cases, a rating was developed for a SonTek 1500 kHz Argonaut-SL, and the instrument was later replaced with the same make, model and frequency. The replacement instrument was deployed at the same location and position and with the

same configuration. Additional SSC samples were collected with the new instrument to evaluate the rating.

- Figure 3 shows data from a site on the Missouri River at Nebraska City, NE.
    - This data was provided by Tim Straub of the USGS (personal communication).
    - The data shows a change in SCB of about +5 dB (for a given SSC) between instrument 1 and instrument 2. There is also a change in the slope of the SSC/SCB relation between the two instruments.
    - The sediment acoustic rating before and after the change is shown below.

      Rating 1: $\log_{10}(SSC) = -2.26 + 0.0651*SCB$

      Rating 2: $\log_{10}(SSC) = -2.28 + 0.0615*SCB$
- Figure 4 shows data from a site on the Trinity River near Wallisville, TX.
    - This data was provided by Zulimar Lucena of the USGS (Lucena and Lee, 2015).
    - The data shows a change in SCB between +5 and -3 dB (for a given SSC) between instrument A and instrument B. There is also a change in the slope of the SSC/SCB relation between the two instruments.
    - The sediment acoustic rating before and after the change is shown below.

      Rating A: $\log_{10}(SSC) = -1.76 + 0.0481*SCB$

      Rating B: $\log_{10}(SSC) = -2.62 + 0.0586*SCB$

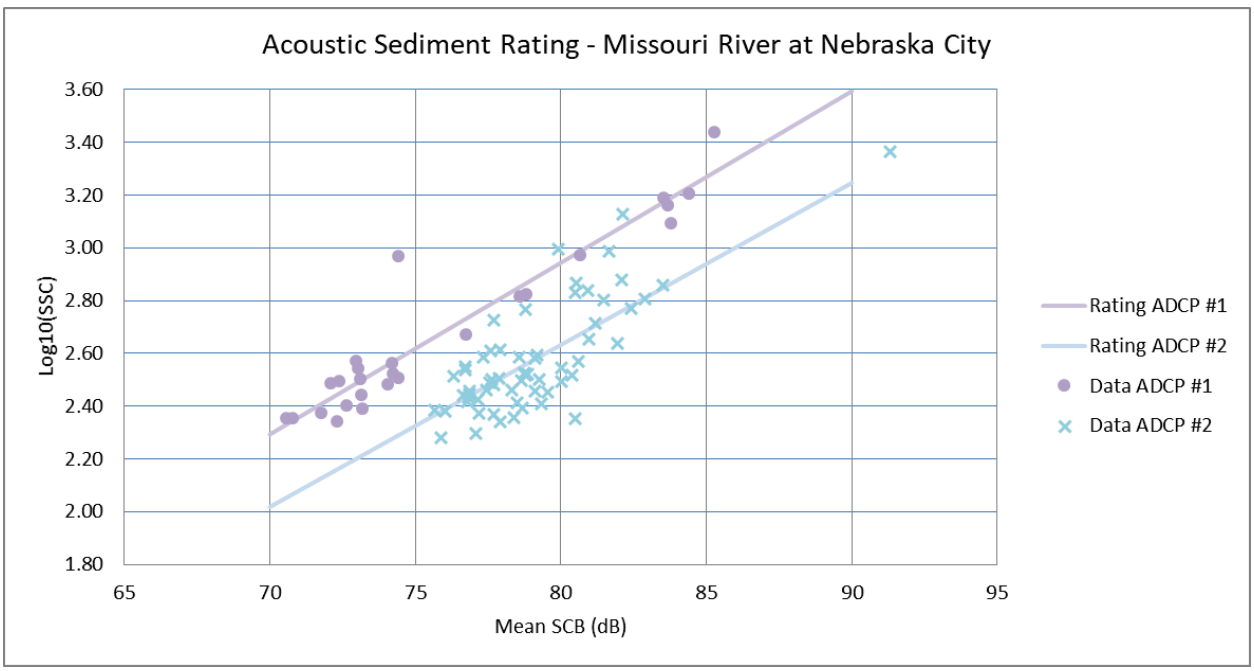


**Figure 3 - Sediment Acoustic Rating: Missouri River at Nebraska City (Straub, written communication, 2019)**

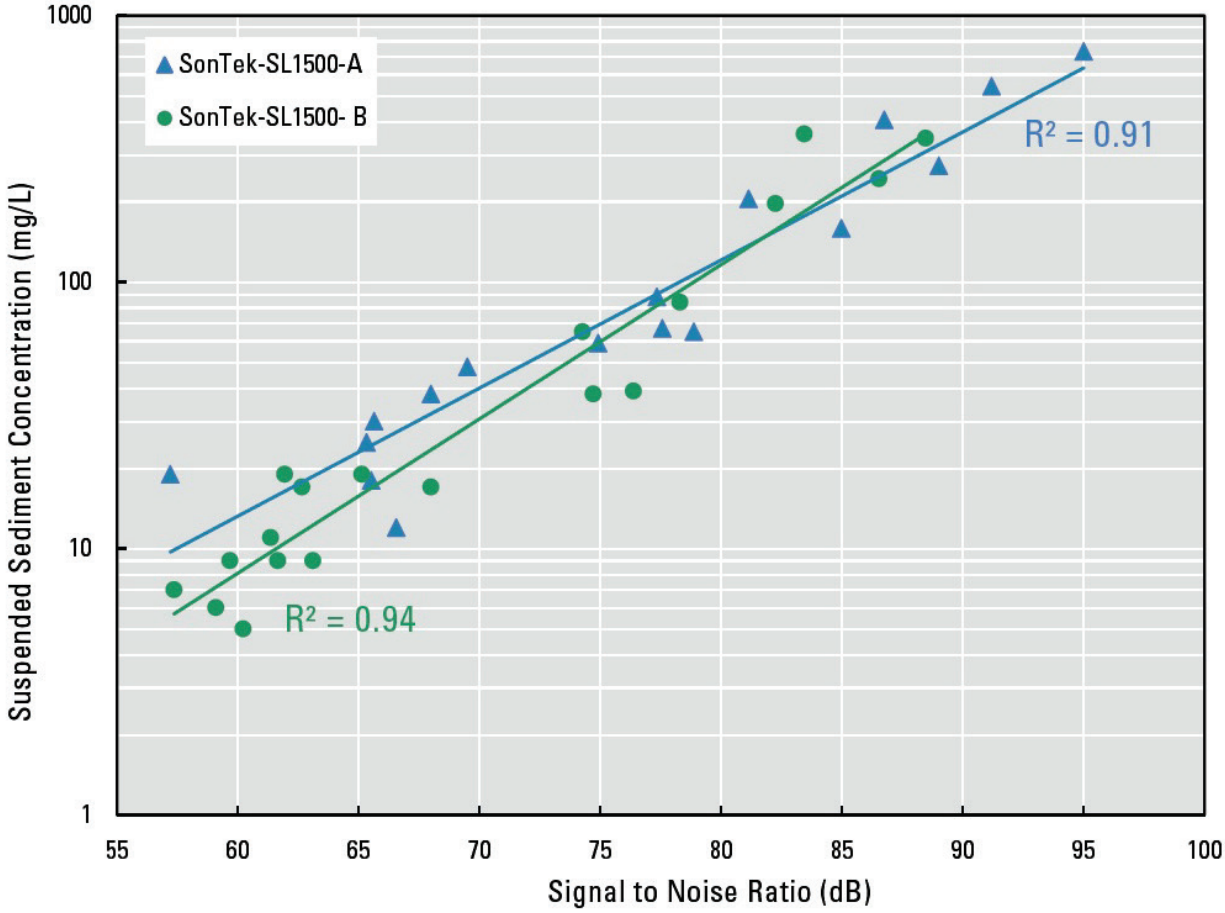


**Figure 4 - Sediment Acoustic Rating: Lower Trinity River near Galveston Bay (Lucena and Lee, 2015)**

Figure 5 and Figure 6 plot the errors that would have resulted at each of these sites if data had not been collected to generate a new sediment acoustic rating for the replacement ADVM.

- At the Missouri River site, SSC would have been biased between +90% to +120% over the range of observed data.
- At the Trinity River site, SSC would have been biased between +80% and -25% over the range of observed data.

These examples show that replacing the ADVM can change both the offset and slope of rating.

- The change in offset could be caused by a change in any or all of the parameters discussed earlier: intensity scale factor (K), source level (SL), backscatter offset ($RL_{OFFSET}$), beam patterns ($b(\theta,\phi)$ and $b'(\theta,\phi)$), or near field response ($\psi_{NF}$).
- A change in slope is assumed to be caused by a change in the intensity scale factor (K), although other components of the ADVM might be involved.

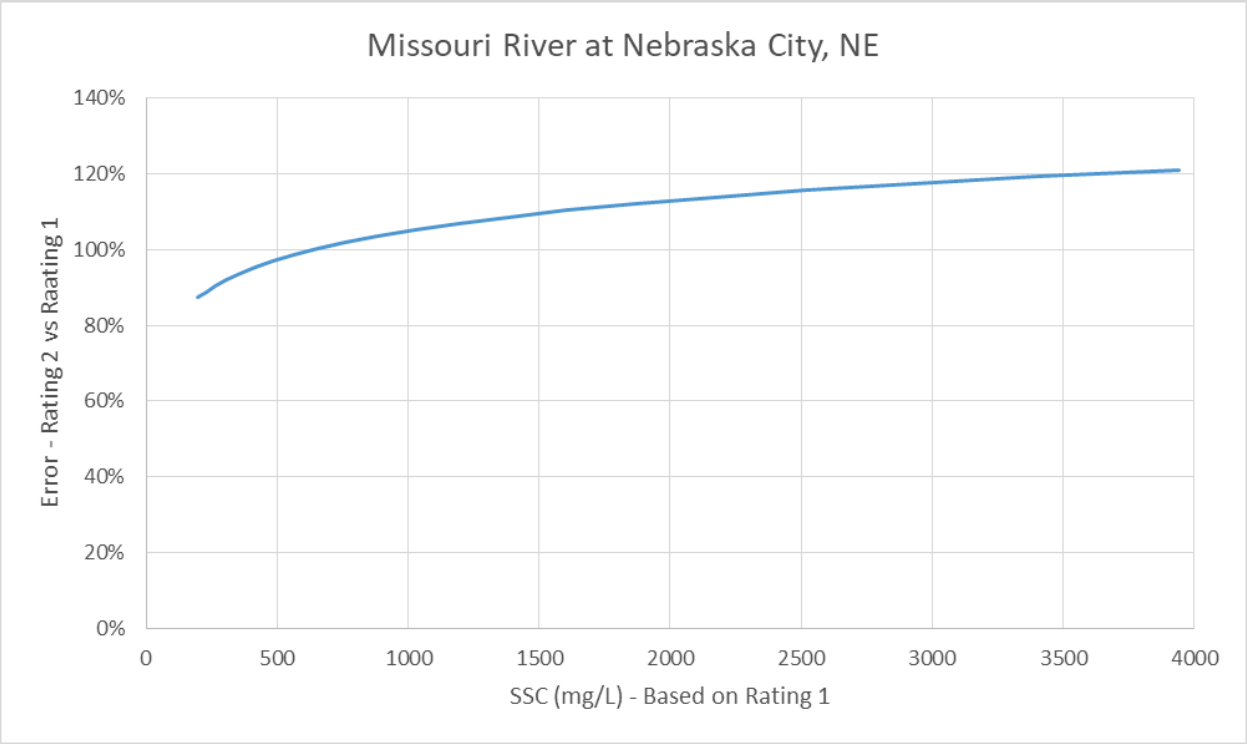


**Figure 5 - SSC Errors Based on Rating Change: Missouri River at Nebraska City, NE**

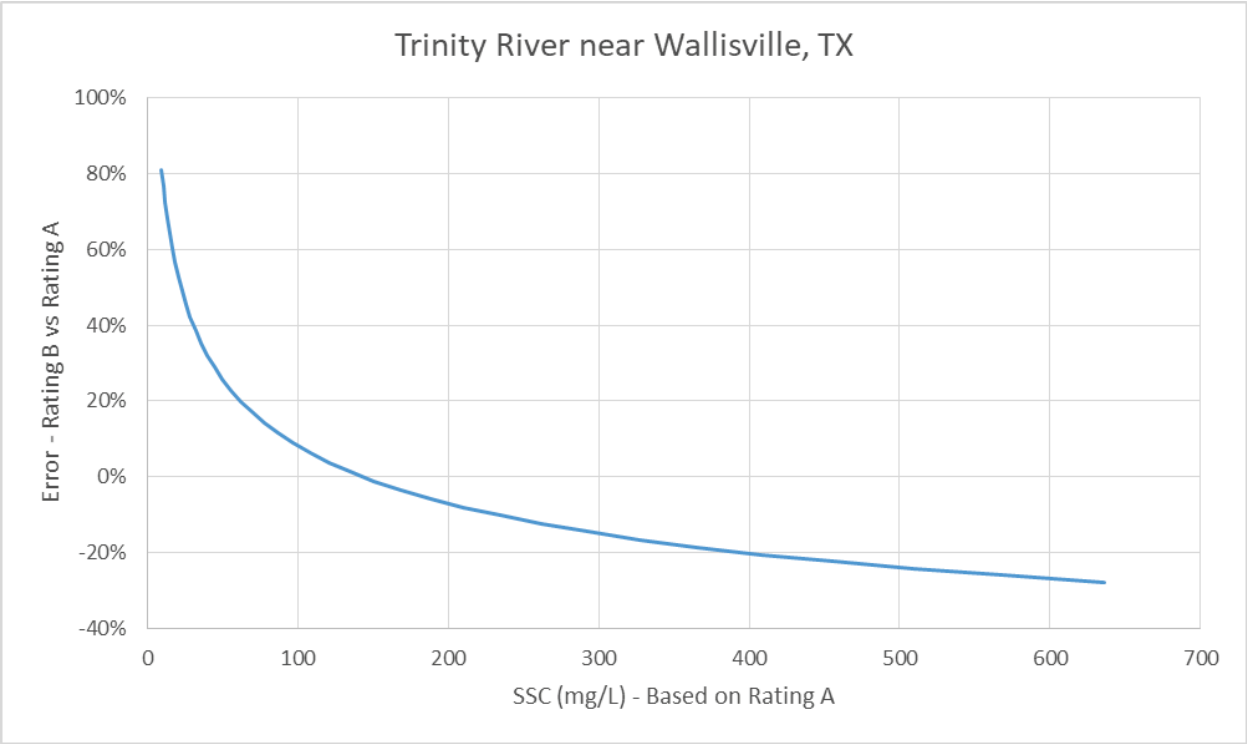


**Figure 6 - SSC Errors Based on Rating Change: Trinity River near Wallisville, TX**

## Acoustic Beam Calibration: Relative and Absolute

Existing processing for a sediment acoustic rating assumes the following parameters are constant.

- Intensity scale factor (K)
- Source level (SL)
- Offset of measured to absolute backscatter ($RL_{OFFSET}$)
- Transmit and receive beam patterns ($b(\theta,\phi)$ and $b'(\theta,\phi)$)
- Near-field transducer response ($\psi_{NF}$)

These assumptions are reliable for an individual ADVM, but not when comparing data from different ADVMs operating at the same frequency.

- K, SL, and $RL_{OFFSET}$ may vary even for the same make, model and frequency.
- Beam patterns and the near-field response can be assumed to be constant for a given model and frequency, but may vary between manufacturers and models.

Two types of acoustic beam calibration could be developed: relative or absolute.

A relative beam calibration would estimate the difference between measured backscatter of ADVMs operating at the same frequency.

- It would estimate the intensity scale factor K.
- It would estimate the offset in functions $F_A$ and $F_B$ that represent total effect of all parameters (K, SL, $RL_{OFFSET}$, $b(\theta,\phi)$, $b'(\theta,\phi)$, $\psi_{NF}$) for two systems A and B.
    - It would not necessarily estimate the effect of each individual parameter, but would estimate the total offset between A and B ($OFFSET_{A\text{-}B} = F_A - F_B$).
    - Measured backscatter from system B would be shifted by $OFFSET_{A\text{-}B}$, and would use the value of K for that system.
    - System B could then apply the sediment acoustic rating developed for A.
- A relative calibration would allow the exchange of different ADVMs, but would not convert the measured data to absolute backscattering.

An absolute calibration would estimate the effect of each parameter on measured backscatter.

- K, SL, and $RL_{OFFSET}$, would be estimated for each ADVM.
- $b(\theta,\phi)$, $b'(\theta,\phi)$, and $\psi_{NF}$ could be determined once for each particular ADVM model and frequency, but would not need to be measured for each system.
- Measured backscatter from a calibrated system could then be converted to absolute backscatter, and could be compared with data from any other system of the same frequency.

For existing sediment acoustic rating procedures, there would be no significant difference between the use of relative and absolute beam calibrations; either would allow for the exchange of calibrated systems. As sediment acoustic monitoring evolves over time, absolute backscatter data may prove beneficial for additional data analysis.

# ADVM Data

## Measurement of Acoustic Backscatter Intensity

The primary function of an ADVM is to measure water velocity based on frequency / phase information from the transducer return signal. The intensity of the return signal varies with distance and conditions in the water; ADVMs generally have a dynamic range of 60-80 dB.

While the receive circuitry varies between different ADVM makes and models, it generally operates on the same basic principles.

- The signal from the transducer is passed into a variable gain amplifier.
    - The amplifier outputs a constant amplitude signal that preserves the frequency / phase information received by the transducer.
    - This signal is used to calculate Doppler shift and the profile of water velocity.
- The circuit outputs an analog signal proportional to the gain applied by the amplifier.
    - This signal is commonly called the Received Signal Strength Indicator (RSSI).
    - The magnitude of the RSSI is proportional to the intensity of the acoustic signal received by the transducers.
    - Given the large dynamic range (60-80 dB), the RSSI normally uses a logarithmic scale, although new systems have been proposed using a linear scale.
- The RSSI signal is sampled by an analog to digital (A/D) converter.
    - The resolution of the resulting data depends on the A/D used.
- This data, which represents the acoustic backscatter intensity, is recorded in counts based on the output of the data from the A/D.
    - This value is then converted to dB using the intensity scale factor (K) specific to each ADVM.

## Manufacturers, Models and Frequencies

Four manufacturers provide ADVMs that have been used by the USGS.

- SonTek
    - SonTek has historically been the largest supplier of side-looking ADVMs. Models include the Argonaut-SL and the SL(3G); these instruments operate at acoustic frequencies of 500, 1500 and 3000 kHz.
    - About 65% of acoustic sediment monitoring sites in a 2012-2013 USGS survey use SonTek instruments.
- NorTek
    - NorTek ADVMs are primarily designed for ocean and coastal use, rather than measurements in rivers. They can be, however, used in these applications.
    - Side-looking models include the AquaDopp and the Easy-Q; the Easy-Q was sold to OTT HydroMet and is now marketed as the SLD (Side Looking Doppler). These instruments operate at acoustic frequencies of 600, 1000 and 2000 kHz.
    - About 20% of sites in the USGS survey use NorTek instruments.
- Teledyne RD Instruments (TRDI)
    - TRDI is the oldest existing manufacturer of ADVMs. Side-looking models include the Channel Master and the Workhorse H-ADCP; these instruments operate at acoustic frequencies of 300, 600 and 1200 kHz.

    - About 15% of sites in the USGS survey use TRDI instruments.
- Rowe Technologies (Rowe)
    - Rowe is one of the newer companies that manufacture ADVMs, although the principals of the company have a long history in the industry. Side-looking models include the River-HQ, which operates at acoustic frequencies of 300, 600, 1200 and 2400 kHz.
    - None of the sites in the USGS survey use Rowe instruments, although a few systems may have been installed since that time.
    - Rowe is developing a prototype three frequency side-looking ADVM specifically for acoustic sediment monitoring (the Horizontal Acoustic Sediment Current Profiler, or H-ASCP). Each H-ASCP will have transducers at 600, 1200 and 2400 kHz. No field results of this system have yet been reported.

**Table 1 - ADVM Manufacturer / Model Summary**

| Manufacturer | Model | Frequencies (kHz) | Intensity Scale Factor (K) (dB/count) |
|---|---|---|---|
| SonTek | SL | 500, 1500, 3000 | 0.43 |
| | SL (3G) | 1500, 3000 | 0.14 |
| TRDI | Channel Master | 300, 600, 1200 | 0.6 |
| | Workhorse H-ADCP | 300, 600, 1200 | 0.42 |
| NorTek / OTT | AquaDopp | 600, 1000, 2000 | 0.43 |
| | Easy-Q / OTT SLD | 600, 1000, 2000 | 0.43 |
| Rowe | River-HQ | 300, 600, 1200, 2400 | Unknown |
| | Prototype H-ASCP | 600 + 1200 + 2400 | ~0.2 |

Table 1 lists a summary of the manufacturers and models of side-looking ADVMs. It also shows typical K values used to convert measured backscatter from counts to dB. Each company also makes vertical profiling ADVMs, generally at the same frequencies and with similar values of K.

## Manufacturer Calibration of Measured Backscatter Data

ADVM measured backscatter is primarily designed as a QA/QC value to evaluate the validity of velocity data; manufacturers perform only limited calibration. A description of the calibration done by each manufacturer is given below. These are based on limited discussions with the manufacturers, and may not accurately represent all procedures.

- SonTek
    - K is estimated during the design phase and is not verified during production.
    - Transmit pulse strength is measured using a test transducer that is mechanically coupled to each ADVM transducer. The voltage measured on the test transducer is compared to expected levels for the system type and frequency.
    - Receive sensitivity is measured by driving the test transducer with a known voltage; this is compared to expected values.
    - Each beam for a given instrument is tuned to provide consistent backscatter data.
    - The noise level of the system is measured by recording signal strength with the system in the air; this is compared to expected values.

- TRDI
    - TRDI did not provide details of the transmit power calibration.
    - The RSSI circuitry is calibrated for a consistent offset and slope between beams within an individual ADVM. TRDI did not provide details for how this calibration was performed.
    - Normally a fixed value of K is used based on estimates during the design phase.
        - Instrument specific K values can be determined during production if requested. It was not clear if a fee is charged for this service.
- NorTek
    - OneFish did not obtain any details on specific calibration procedures. It is reasonable to assume that procedures are similar to those used by SonTek.
- Rowe
    - OneFish did not obtain any details on specific calibration procedures.

While production methods are sufficient when using measured backscatter for QA/QC, they have significant limitations when using measured backscatter for sediment monitoring.

- There can be an offset in the measured backscatter data of different beams within an individual ADVM.
    - OneFish estimates this offset might be as much as ±2-3 dB.
- The offset may be larger between different systems of the same make and model.
    - OneFish estimates this offset might be as much as ±4-5 dB.
- The intensity scale factor (K) may vary.
    - It is assumed that changes in K are caused by small variations in the RSSI components. While the transducers and other components may have some impact, they are likely to be insignificant.
    - Systems from SonTek and NorTek typically use a single receive channel for all beams; this is done to reduce the size and complexity of the system electronics.
        - Since the same RSSI components are used, the value of K should not change significantly between beams within an individual ADVM.
    - Systems from TRDI and Rowe typically use a separate receive channel for each beam; this is done to maximum the rate at which the system can collected data.
        - Since different RSSI components are used, the value of K may change between beams within an individual ADVM.
    - The value of K between different systems of the same make/model can vary. Based on tests OneFish personnel have run in the past, a variation of as much as ±10% is possible.
- The production process does not account for any non-linearity in the RSSI signal.
    - The manufacturers using a constant value of K to convert from counts to dB over the full dynamic range.
    - Based on tests OneFish personnel have run in the past, non-linear performance of as much as ±1-2 dB is possible.

Based on this, OneFish would expect that measured backscatter between different instruments of the same make, model and frequency might be offset by up to ±5 dB, and the correct value of K could vary ±10% or more. This variation directly affects the sediment acoustic ratings shown in Equation 4 and Equation 5.

# Beam Calibration Techniques

## Calibration Goals

The goal of calibration is to provide measured backscatter from an ADVM such that a system can be replaced with the same make, model and frequency without requiring changes to the sediment acoustic rating. Ideally this would apply to any system operating at the same acoustic frequency, independent of the make or model.

The calibration must correct for potential changes in both the slope and offset of the sediment acoustic rating. Changes in the offset can be caused by multiple factors while changes in the slope are most likely related to the intensity scale factor (K).

## Potential Methods

OneFish considered multiple potential methods for beam calibration.

- Suspended sediment tank
  - A special laboratory tank would be built to maintain a known SSC in a volume of water sufficient for data collection with the ADVM.
  - Measured backscatter from different instruments with the same SSC and sediment type could be compared.
- Discreet target
  - The ADVM would be installed in a laboratory tank, and an individual acoustic target would be suspended in the water at a fixed distance. The target is typically a sphere of metal or other material. Measured backscatter from the target would then be compared between different systems.
  - Selection, installation and measured of the discreet target is challenging, but has been successfully done (Foote and Martini, 2010).
- In-situ
  - Reference ADVMs would be maintained for each make, model and frequency.
  - The reference systems would be temporarily installed at a site next to the instrument to be calibrated. Measured backscatter from the reference system would be compared to the installed ADVM. Parallel data collection would be conducted long enough to observe a range of conditions in the river.
- Electronics only
  - Probes would be connected directly to the electronics of the ADVM.
  - These would measure the magnitude of the electrical transmit pulse, and feed signals of a known strength into the receive electronics. Results could then be compared between different systems.
- Test transducer
  - A test transducer would be coupled to the face of each ADVM transducer with an acoustically conductive material (i.e. silicon gel).
  - A variety of test transducer designs are possible; one option would be to purchase bare ADVM transducers from the instrument manufacturers.
  - The magnitude of the transmit pulse would be measured on the test transducer; it would then be driven by a signal of known strength and backscatter data would be recorded. Results could then be compared between different systems.

- Reference hydrophone
    - The ADVM would be installed in a laboratory tank with a reference hydrophone mounted a fixed distance away.
    - The hydrophone would be calibrated for both transmit and receive operation.
        - In receive mode, the voltage output by the hydrophone can be directly converted to the acoustic pressure at its face.
        - In transmit mode, the hydrophone is driven at a known frequency with a signal of known strength. The acoustic pressure at a fixed distance (1 m) from the face of the hydrophone can be computed.
    - The absolute transmit power and receive sensitivity, based on the physical pressure in the water, can be determined. These values can then be directly compared between different ADVMs.

**Table 2 - Calibration Method Comparison**

| Method | Calibration Quality | Advantages | Disadvantages |
|---|---|---|---|
| Suspended sediment tank | • Offset: fair<br>• Slope: fair<br>• Absolute calibration: no | • Direct calibration from suspended sediment<br>• Ability to control SSC and sediment size / type | • Difficult to design, operate and maintain test tank<br>• Inherent noise in the data<br>• Time consuming procedure |
| In-situ | • Offset: good<br>• Slope: fair<br>• Absolute calibration: no | • Direct calibration from suspended sediment<br>• No need to remove ADVM from field installation | • Difficulty in aligning measurement volumes<br>• Time consuming<br>• Need to maintain reference systems for long periods<br>• Inherent noise in the data<br>• Limited ability to calibrate at a range of backscatter |
| Discrete target | • Offset: fair/good<br>• Slope: poor<br>• Absolute calibration: theoretical | • Direct calibration of backscatter data | • Difficult design and operation of test procedure<br>• Limited ability to calibrate at a range of backscatter values |
| Electronics only | • Offset: fair<br>• Slope: good<br>• Absolute calibration: no | • Electrical parameters are easy to measure and control<br>• Can calibrate full receiver dynamic range | • Ignores variations in transducer performance<br>• Requires opening ADVM to access electronics |
| Test transducer | • Offset: fair/good<br>• Slope: fair/good<br>• Absolute calibration: no | • Simple testing procedure<br>• Electrical parameters are easy to measure and control<br>• Can calibrate full receiver dynamic range | • Test transducers can vary<br>• Effectiveness of mechanical coupling can vary<br>• Effective accuracy would need to be verified |
| Reference hydrophone | • Offset: good<br>• Slope: good<br>• Absolute calibration: yes | • Direct measurement of acoustic pressure<br>• Includes entire ADVM system<br>• Can calibrate full receiver dynamic range<br>• Can measure transmit and receive beam pattern and near-field response | • Requires relatively large tank and reference hydrophone<br>• Needs adjustable mounting systems as well as electronics / data collection platform<br>• Relatively time consuming procedure<br>• Concern about systems above 2000 kHz |

Table 2 compares the potential calibration methods.

- OneFish recommends eliminating the first four options.
    - Operating of a suspended sediment tank is inherently difficult, especially to maintain consistent performance over time.
    - In-situ calibration would be time consuming, and could fail in the long run if reference systems become damaged. It also has limited potential to measure the intensity scale factor (K).
    - Discrete target calibration is difficult, and has limited potential to measure K.
    - Electronics only calibration ignores the performance of the transducers, which could introduce an unacceptable level of uncertainty.
- The test transducer calibration has limitations, but might provide sufficient accuracy for effective calibration.
    - It would provide relatively rapid calibration of individual ADVMs. OneFish would estimate 2-3 hours per system once the procedure is developed.
    - It could provide data over the full receiver dynamic range, allowing direct measurement of K.
    - Test transducers and the method of mechanical coupling would need to be designed and verified on multiple systems.
        - Testing with real-world reference data would need to be performed to evaluate if the procedure can achieve the required accuracy and reliability.
        - Test transducers would need to be maintained for each frequency to ensure the ability to calibrate and maintain systems over time.
    - This method would not provide absolute acoustic backscatter data, but would allow data from systems to be directly compared to one another.
- The reference hydrophone calibration is likely to provide the best performance over the longest period of time.
    - This method provides direct conversion of ADVM data to the acoustic pressure in the water, and can be used to calculate absolute backscattering.
    - Calibrated hydrophones are readily available, and can be maintained over time by independent testing facilities.
    - This method can also measure other acoustic parameters of the ADVM including transmit and receive beam patterns, and the near-field response.
    - This method will require notable effort up front to build the required mounting and electrical systems, and to develop reliable calibration procedures. OneFish estimates this would require 2-3 personnel, 1-2 weeks of laboratory work, plus additional time for preparation, analysis and documentation.
    - Once a procedure is established, OneFish estimates calibration of a two beam ADVM would take two people one day of laboratory time, plus additional time for data analysis.
    - The best hydrophones have a maximum calibrated frequency of 2000 kHz, less than the maximum ADVM frequency of 3000 kHz. It may still be possible to use these hydrophones at the higher frequencies, as will be discussed later.

OneFish recommends the reference hydrophone calibration method, as it provides the best quality calibration and should be able to be maintained reliably for many years. Details of how this calibration could be implemented are provided in the section below.

## Reference Hydrophone Calibration

### Calibration Procedure

The reference hydrophone calibration procedure is outlined below.

- The ADVM and hydrophone would be mounted in a large tank of water.
    - The ADVM beam to be calibrated would be aimed along the axis of the tank.
    - Other ADVM beams would have dampening installed to prevent additional energy in the water that could affect measurements.
    - The distance between the two would be selected to be outside the near-field of the ADVM but within its normal profiling range.
        - The near field distance depends on the ADVM frequencies and transducer size. It varies from less than 0.5 m for high frequency systems (i.e. 3000 kHz), to more than 2 m for lower frequency systems (i.e. 500 kHz).
        - The mounting distance might be 1-4 m depending on frequency.
- The instruments would be carefully aligned in the center of their beams.
    - The ADVM and hydrophone would need to be rotated about both their horizontal and vertical axes to achieve the best alignment. The alignment would be done with the hydrophone in both transmit and receive modes.
- Data collection with the ADVM would be started using most of the same operating parameters used in the field.
    - The one exception might be the averaging time, which would be set to a shorter value (perhaps 5-20 seconds).
- In receive mode, the hydrophone would measure the intensity of the transmit pulse.
    - The hydrophone calibration would be used to relate its measured voltage to the pressure in the water. After accounting for range, this would give the source level (SL) of the transducer.
- In transmit mode, the hydrophone would output a continuous signal at the desired frequency.
    - Based on the amplitude of the voltage driving the hydrophone, the physical pressure in the water can be calculated. After accounting for distance, this gives the pressure in the water at the ADVM transducer face.
    - Measured backscatter can then be directly related to pressure in the water.
    - The measurements would be repeated at different of voltage / pressure levels over as much of the dynamic range of the ADVM as possible. This would allow precise calculation of the intensity scale factor (K).
- Transmit and receive pressures, along with other system parameters and corrections, can be used to calculate absolute backscattering. The resulting data should be consistent for any instrument operating at the same frequency.

When initially developing the test procedures, it may be helpful to measure other parameters to assist in data analysis and to evaluate some of the assumptions inherent with using acoustics to monitor suspended sediment.

- The transmit and receive beam patterns of the ADVM transducer
- Non-linearities in the ADVM receive sensitivity
- Variations in transmit/receive data with distance, particularly the near-field response

## Hydrophone Providers

Most ADVMs operate at frequencies from 300 to 3000 kHz. Many hydrophone applications occur at lower frequencies, and are receive only and do not require the hydrophone to transmit a calibrated signal. This limits the number of potential suppliers.

OneFish reviewed and contacted a variety of commercial hydrophone suppliers, but none of them provide a suitable product. These included Precision Acoustics, Onda Corporation, Teledyne Reson, Teledyne Benthos, Bruel and Kjaer (B&K), SonarTech, and Zetlab.

OneFish recommends hydrophone supplied by the U.S. Navy Underwater Sound Reference Division (USRD).

- The USRD acts as the equivalent of the National Institute of Standards and Testing (NIST) for underwater sound applications. They provide a variety of hydrophones for commercial, governmental and military applications.
- Two USRD hydrophones operate at the range of frequencies required by ADVMs:
    - E8 (200 to 2000 kHz)
    - E37 (100 to 2000 kHz) – this includes a switchable pre-amplifier
    - The E8 is likely the best option but this should be considered more closely when designing the calibration procedure.
- These hydrophones are calibrated to a maximum frequency of 2000 kHz.
    - Some ADVMs operate at frequencies up to 3000 kHz.
    - Based on discussions with the USRD, the hydrophone may provide reliable performance up to 3000 kHz.
    - The absolute accuracy of the hydrophone will be lower, however it may be able to provide consistent results that allow data from different ADVMs at these higher frequencies to be compared.
    - Performance of the hydrophone at these higher frequencies will need to be tested to verify they can provide a reliable calibration.
- USRD hydrophones are leased on an annual basis; the price includes annual calibration.
    - Current prices are $2,875/year for the E8 and $4,025/year for the E37.

Below is contact information for the USRD.

Steven Crocker, Ph.D.
Naval Undersea Warfare Center
Underwater Sound Reference Division
1176 Howell Street, Newport, RI 02841
401-832-6131 (Office)
401-595-7255 (Mobile)
Email steven.crocker@navy.mil

## Testing Facilities

To implement a reference hydrophone calibration for ADVMs, a testing tank meeting the following criteria would be needed.

- 2 m wide, 2 m deep, and 4 m long
    - Higher frequency ADVMs would need a tank only 2 m long, but lower frequencies would need more space
- Stationary, clear water
- Ability install and manipulate the ADVM and hydrophone
- Easy access to a reasonable workspace, including AC power

OneFish considered a number of facilities at which the testing could be performed.

- USGS Hydrologic Instrumentation Facility (HIF)
    - OneFish discussed the project with Scott Kimball from the HIF.
    - While they do not currently perform this type of testing, it is within the capability of their facilities and technicians.
    - They do not currently have a reference hydrophone, and would need to lease one. This is a straight forward process.
    - The HIF has two potential tanks: the large tow tank and the jet tank.
        - The tow tank large enough to calibrate any ADVM. It is in regular use for current meter calibration, so access could be limited.
        - The jet tank is ~3 m long and could be used for higher frequency systems. It is not commonly used, and would be available for this application.
    - After developing the required measurement equipment and mounting fixtures, OneFish estimates the following time would be required.
        - 1-2 weeks of laboratory time, with 2-3 people, for initial tests to characterize 3-4 ADVM models / frequencies
        - One day of laboratory time, with one people, to calibrate a two beam ADVM, once the procedure is established
- USRD
    - The USRD operates and maintains a number of tanks and facilities. The most appropriate for this application would be the Acoustic Open Tank Facility (OTF) located in Newport, RI.
    - This facility maintains multiple reference hydrophones and is readily familiar with their operation.
    - Based on preliminary conversations, OneFish estimates the following costs to have the calibrations performed at the USRD facility.
        - An upfront cost of $25,000-$30,000 would be required for initial tests and to characterize 3-4 different ADVM models / frequencies. 1-2 personnel should be on-site to participate in these tests in addition to USRD technicians.
        - Once the procedure is established, calibration of a two beam ADVM would cost $5,000-$6,000 and would take 1 day. It may or may not be necessary to have someone present for the testing.
    - USRD would provide the raw data collected; analysis of this data and final calibration of the ADVM would need to be performed by others.

- University of New Hampshire Jere A. Chase Ocean Engineering Lab
    - This facility is located in Durham, NH and has a number of suitably sized tanks.
    - While they do work with acoustics, they rarely work above 400 kHz and do not currently have reference hydrophones at the required frequencies.
    - It might be possible to work with this facility to generate the capability for these tests, however the HIF and USRD are better candidates at this time.
- Instrument manufacturers
    - OneFish discussed with each manufacturer to see if they have the potential and willingness to provide calibration for a fee.
    - NorTek is likely unwilling as they no longer focus on this market.
    - SonTek, TRDI and Rowe all have tanks that could be used for calibration. None of these companies currently keeps a calibrated reference hydrophone, so they would need to purchase or lease an appropriate system.
    - Calibration would require up-front investments plus expenses for each system.
        - They would likely expect at least some reimbursement for up-front costs, which might be in the range of $20,000 to $90,000.
        - The cost to calibrate an individual ADVM might be $1,500 to $4,000.
    - Each company would calibrate only their own instruments. There could be problems calibrating older systems as newer models are introduced.
    - OneFish does not recommend this option considering the use of multiple facilities, and uncertainty in the availability of the service over time.

OneFish assumes the HIF would be the most appropriate facility, as it would allow the USGS to maintain full control of the calibration process. The USRD would also be a viable candidate.

## Measurement, Mounting and Data Collection

A number of items would need to be designed and built in order to conduct these tests.

- Hydrophone receive measurements
    - This determines the transmit power of the ADVM, and requires measuring the voltage output by the hydrophone when it receives the transmit pulse.
    - This might be as simple as a high quality digital oscilloscope, although a more automated system might save time in the long run.
- Hydrophone transmit signals
    - A circuit will need to be developed to generate a transmit signal with variable amplitude at the desired frequency. The range of signal amplitude is likely to be on the order of 0.001 to 10 V peak-to-peak.
    - It is essential for the circuit to be accurate and linear over a wide range. It would likely use a frequency generator with additional components to control signal strength.
- Mounting
    - Mounts will need to be fabricated for both the ADVM and the hydrophone.
    - Mounts need to be easily adjustable in the depth as well as rotation about the horizontal and vertical axes.
    - Ideally rotation should be able to be controlled with resolution on the order of 0.1º, particularly for measurements of the ADVM beam pattern.

    - The ADVM mount will need to accommodate different ADVM types and frequencies, and will need to be adjustable to align different beams along the axis of the tank.
    - The distance between the two systems will need to be adjustable.
- Dampeners should be designed to install over the ADVM transducers not being tested to prevent additional energy from affecting measurements in the tank.
- System control and data analysis
    - The ADVM will need to be programmed and data collection started. This might use the manufacturer's software or a direct, custom interface with the system.
    - The timing of each ADVM sample should be controlled, perhaps using SDI-12.
    - The recorded data will need to be downloaded, and measured backscatter data extracted to be compared with the known pressure at the ADVM transducer (based on the hydrophone operation).
    - Once all data has been collected, it will be analyzed to determine the source level, receive sensitivity, intensity scale factor (K), and other parameters. A final calibration report should be generated in a form that can be readily incorporated into the standard sediment acoustic rating procedure.

## Calibration Error Analysis

It is important to ensure that the accuracy of the calibration procedure is sufficient so that the difference between systems does not have a significant impact on the measurement of suspended sediment. This section presents a simplified analysis of calibration errors; a more complete analysis may be appropriate in the future.

Errors in the calibration procedure will produce a consistent difference in measured backscatter between two ADVMs. This will result in a bias in the calculated SSC when an instrument is replaced.

The basic relationships between SSC and measured backscatter are shown in Equation 4 and Equation 5. For simplicity, this section will use the simpler relationship from Equation 5 between SSC and SCB.

For this analysis, the true SCB (in dB) is given by $A_{TRUE}$, and the calibration has introduced an error $A_{ERR}$ so that the reported SCB is ($A_{TRUE} + A_{ERR}$). The true and reported values of SSC can be calculated and compared as shown in Equation 6 below.

$$\frac{SSC_{REPORTED}}{SSC_{TRUE}} = \frac{10^{b0+b1*(A_{TRUE}+A_{ERR})}}{10^{b0+b1*A_{TRUE}}} = 10^{b1*A_{ERR}}$$

**Equation 6 - Calibration Error Analysis (Simplified)**

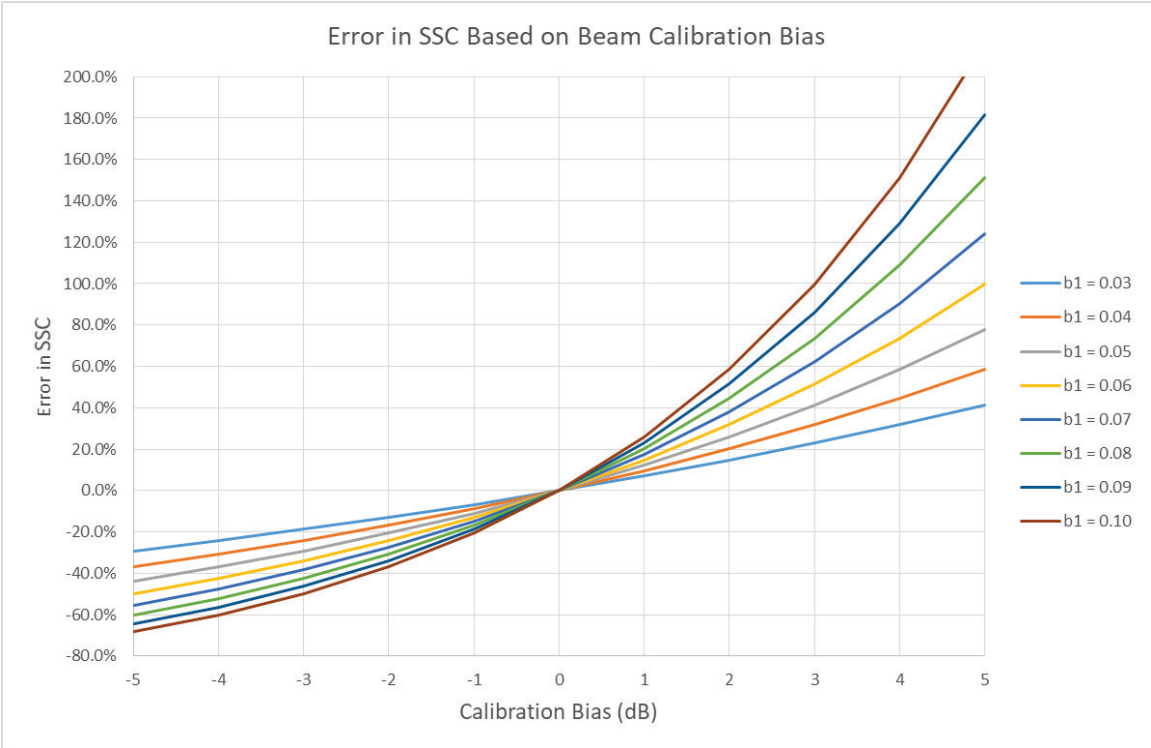


**Figure 7 - Error in SSC Based on Beam Calibration Error**

Figure 7 plots the errors in SSC based for different error in the beam calibration.

- The error in SSC is a function of both the error in SCB, and the slope of the sediment acoustic rating ($b_1$).
- Figure 7 plots SSC error for the anticipated range of $b_1$ from 0.03 to 0.10.

The USRD calibration and measurement capability certificate (Appendix A) estimates the following expanded uncertainties for their hydrophones (95% confidence interval).

- Hydrophone transmit: 0.8 to 2 dB, depending on frequency
- Hydrophone receive: 0.6 to 1 dB, depending on frequency
- The total uncertainty in the combined transmit and receive calibration will depend on the frequency of the ADVM.
    - < 1000 kHz: ~1 dB
        - SSC errors from roughly -15% to +25%
    - > 1000 kHz: 2-3 dB
        - SSC errors from roughly -30% to +50%

The potential errors here are significant, and raise some questions about whether this calibration will prove effective. However, the uncertainties listed above relate to the absolute calibration of the hydrophone – its ability to convert voltage directly to the physical pressure in the water.

For the effectiveness of the calibration, a more important consideration is the consistency and stability of the hydrophone response. OneFish discussed this with Steve Crocker from USRD, who offered the following observations.

- Many individual hydrophones have been in use for 10-20 year or more, and have been calibrated on an annual basis throughout that time. Customers often continue to use the same hydrophone for many years.
- The calibration of an individual hydrophone is generally stable within the measurement limitations of the USRD equipment. Steve estimated this stability to be on the order of a few tenths of a dB.
- If the same hydrophone is used for each calibration, the stability of that hydrophone will determine the extent to which data can be compared between different instruments.
    - This uncertainty should be on the order of a few tenths of a dB, much lower than the absolute hydrophone specifications.
    - This would correspond to errors in SSC on the order of ±5-10%.
- The resolution of measured backscatter for most ADVMs is ~0.4 dB, although some models have resolution ranging from 0.14 to 0.6 dB.
    - This resolution of measured backscatter is roughly equal to the estimated stability of the hydrophone.
    - This measurement resolution may therefore represent the lowest potential uncertainty for any calibration procedure.

## References

This report does not provide a detailed review of acoustic suspended sediment monitoring literature. It primarily refers to USGS reports which provide a detailed review of the methodology, and a more complete list of references. OneFish has not attempted to provide references to the original source material.


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Lucena, Z., Lee, M.T., April 22, 2015. "Comparing Acoustic Surrogate Models for Monitoring Sediment Supply to Galveston Bay, Texas." 10th Federal Interagency Sedimentation Conference. Reno, Nevada.

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## Appendix A: USRD Calibration and Measurement Capabilities

*See following pages.*

# National Voluntary Laboratory Accreditation Program

**CALIBRATION LABORATORIES** **NVLAP LAB CODE 600189-0**

## SCOPE OF ACCREDITATION TO ISO/IEC 17025:2005

| **NUWC Underwater Sound Reference Division** | **Fields of Calibration** |
|---|---|
| 1176 Howell Street<br>Code 1531, Building 1171A<br>Newport, RI 02841-1708<br>Dr. Victor F. Évora<br>Phone: (401) 832-8475 Fax: (401) 832-4989<br>E-mail: victor.m.evora@navy.mil<br>URL: http://www.navsea.navy.mil/Home/Warfare-Centers/NUWC-Newport/What-We-Do/Detachments/Underwater-Sound-Reference-Division/ | Mechanical |

**CALIBRATION AND MEASUREMENT CAPABILITIES (CMC)** Notes 1,2

| **Measured Parameter or Device Calibrated** | **Range** | **Expanded Uncertainty ($k$=2)** Note 3,5 | **Remarks** |
|---|---|---|---|
| **THERMODYNAMIC** | | | |
| **ACOUSTICS (20/M05)** | | | |
| Free-field sensitivity level of reference measuring hydrophones | (dB re 1V/µPa) | | Three-transducer spherical wave reciprocity<br>Open tank method<br>(ANSI/ASA S1.20:2012) |
| 1 kHz to 80 kHz | -230 to -140 | 0.4 dB | |
| >80 kHz to 1.25 MHz | | 0.6 dB | |
| >1.25 MHz to 2 MHz | | 1 dB | |
| | (dB re 1V/µPa) | | Comparison-Replacement Free-field<br>Open tank method<br>(ANSI/ASA S1.20:2012) |
| 1 kHz to 50 kHz | -230 to -140 | 0.6 dB | |
| >50 kHz to 1 MHz | | 0.8 dB | |
| >1 MHz to 2 MHz | | 2 dB | |

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**CALIBRATION AND MEASUREMENT CAPABILITIES (CMC)** Notes 1,2

| Measured Parameter or Device Calibrated | Range | Expanded Uncertainty ($k$=2) Note 3,5 | Remarks |
|---|---|---|---|
| Pressure sensitivity level of reference measuring hydrophones | | | Coupler reciprocity: Primary (IEC-60565) Temperature: -3 °C to 40 °C Pressure: 0.345 MPa to 13.8 MPa |
| | (dB re 1V/µPa) | | |
| 3 Hz to 10 Hz | -190 to -170 | 0.3 dB | |
| >10 Hz to 2000 Hz | | 0.2 dB | |
| | | | Side-by-side method; closed test chamber (ANSI/ASA S1.20:2012) Temperature: 0 °C to 35 °C Pressure: 0.345 MPa to 13.8 MPa |
| | (dB re 1V/µPa) | | |
| 3 Hz to 800 Hz | -230 to -140 | 0.5 dB | |
| >800 Hz to 1250 Hz | | 0.6 dB | |
| >1250 Hz to 1600 Hz | | 0.9 dB | |
| Directional response of reference measuring hydrophones | | | Open tank method (ANSI/ASA S1.20:2012) |
| | $ka \leq 40$ (dB, normalized) | | |
| 1 kHz to 2 MHz | 0 to -3 | 0.2 dB | |
| | > -3 to -6 | 0.3 dB | |
| | > -6 to -10 | 0.5 dB | |
| | -10 to -20 | 1 dB | |
| | > -20 to -40 | 2 dB | |
| | > -40 to -50 | 4 dB | |
| | > -50 to -60 | 6 dB | |
| | $40 < ka \leq 80$ (dB, normalized) | | |
| 10 kHz to 2 MHz | 0 to -3 | 0.2 dB | |
| | > -3 to -6 | 0.5 dB | |
| | > -6 to -10 | 0.9 dB | |
| | > -10 to -30 | 3 dB | |
| | > -30 to -40 | 6 dB | |
| | > -40 to -60 | 7 dB | |

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**CALIBRATION AND MEASUREMENT CAPABILITIES (CMC)** [Notes 1,2]

| Measured Parameter or Device Calibrated | Range | Expanded Uncertainty ($k$=2) [Note 3,5] | Remarks |
|---|---|---|---|
| Transmit voltage response of acoustic projectors | (dB re 1 µPa·m/V) | | Open tank method (ANSI/ASA S1.20:2012) |
| 1 kHz to 63 kHz | 70 to 200 | 0.7 dB | |
| >63 kHz to 800 kHz | | 0.8 dB | |
| >800 kHz to 1 MHz | | 0.9 dB | |
| >1 MHz to 2 MHz | | 2 dB | |
| Transmit current response of acoustic projectors | (dB re 1 µPa·m/A) | | Open tank method (ANSI/ASA S1.20:2012) |
| 1 kHz to 63 kHz | 140 to 200 | 0.7 dB | |
| >63 kHz to 800 kHz | | 0.8 dB | |
| > 800 kHz to 1 MHz | | 0.9 dB | |
| >1 MHz to 2 MHz | | 2 dB | |
| Directional response of acoustic projectors | $ka \leq 40$ (dB, normalized) | | Open tank method (ANSI/ASA S1.20:2012) |
| 1 kHz to 2 MHz | 0 to -3 | 0.2 dB | |
| | > -3 to -6 | 0.3 dB | |
| | > -6 to -10 | 0.5 dB | |
| | > -10 to -20 | 1 dB | |
| | > -20 to -40 | 2 dB | |
| | > -40 to -50 | 4 dB | |
| | > -50 to -60 | 6 dB | |
| 10 kHz to 2 MHz | $40 < ka \leq 80$ (dB, normalized) | | |
| | 0 to -3 | 0.2 dB | |
| | > -3 to -6 | 0.5 dB | |
| | > -6 to -10 | 0.9 dB | |
| | > -10 to -30 | 3 dB | |
| | > -30 to -40 | 6 dB | |
| | > -40 to -60 | 7 dB | |
| **END** | | | |

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| Notes |
|---|
| **Note 1:** A Calibration and Measurement Capability (CMC) is a description of the best result of a calibration or measurement (result with the smallest uncertainty of measurement) that is available to the laboratory's customers under normal conditions, when performing more or less routine calibrations of nearly ideal measurement standards or instruments. The CMC is described in the laboratory's scope of accreditation by: the measurement parameter/device being calibrated, the measurement range, the uncertainty associated with that range (see note 3), and remarks on additional parameters, if applicable.<br><br>**Note 2:** Calibration and Measurement Capabilities are traceable to the national measurement standards of the U.S. or to the national measurement standards of other countries and are thus traceable to the internationally accepted representation of the appropriate SI (Système International) unit.<br><br>**Note 3:** The uncertainty associated with a measurement in a CMC is an expanded uncertainty with a level of confidence of approximately 95 %, typically using a coverage factor of $k = 2$. However, laboratories may report a coverage factor different than $k = 2$ to achieve the 95 % level of confidence. Units for the measurand and its uncertainty are to match. Exceptions to this occur when marketplace practice employs mixed units, such as when the artifact to be measured is labeled in non-SI units and the uncertainty is given in SI units (Example: 5 lb weight with uncertainty given in mg).<br>**Note 3a:** The uncertainty of a specific calibration by the laboratory may be greater than the uncertainty in the CMC due to the condition and behavior of the customer's device and specific circumstances of the calibration. The uncertainties quoted do not include possible effects on the calibrated device of transportation, long term stability, or intended use.<br>**Note 3b:** As the CMC represents the best measurement results achievable under normal conditions, the accredited calibration laboratory shall not report smaller uncertainty of measurement than that given in a CMC for calibrations or measurements covered by that CMC.<br>**Note 3c:** As described in Note 1, CMCs cover calibrations and measurements that are available to the laboratory's customers under *normal conditions.* However, the laboratory may have the capability to offer special tests, employing special conditions, which yield calibration or measurement results with lower uncertainties. Such special tests are not covered by the CMCs and are outside the laboratory's scope of accreditation. In this case, NVLAP requirements for the labeling, on calibration reports, of results outside the laboratory's scope of accreditation apply. These requirements are set out in Annex A.5. of NIST Handbook 150, Procedures and General Requirements.<br><br>**Note 4:** Uncertainties associated with field service calibration may be greater as they incorporate on-site environmental contributions, transportation effects, or other factors that affect the measurements. (This note applies only if marked in the body of the scope.)<br><br>**Note 5:** Values listed with percent (%) are percent of reading or generated value unless otherwise noted.<br><br>**Note 6:** NVLAP accreditation is the formal recognition of specific calibration capabilities. Neither NVLAP nor NIST guarantee the accuracy of individual calibrations made by accredited laboratories. |

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