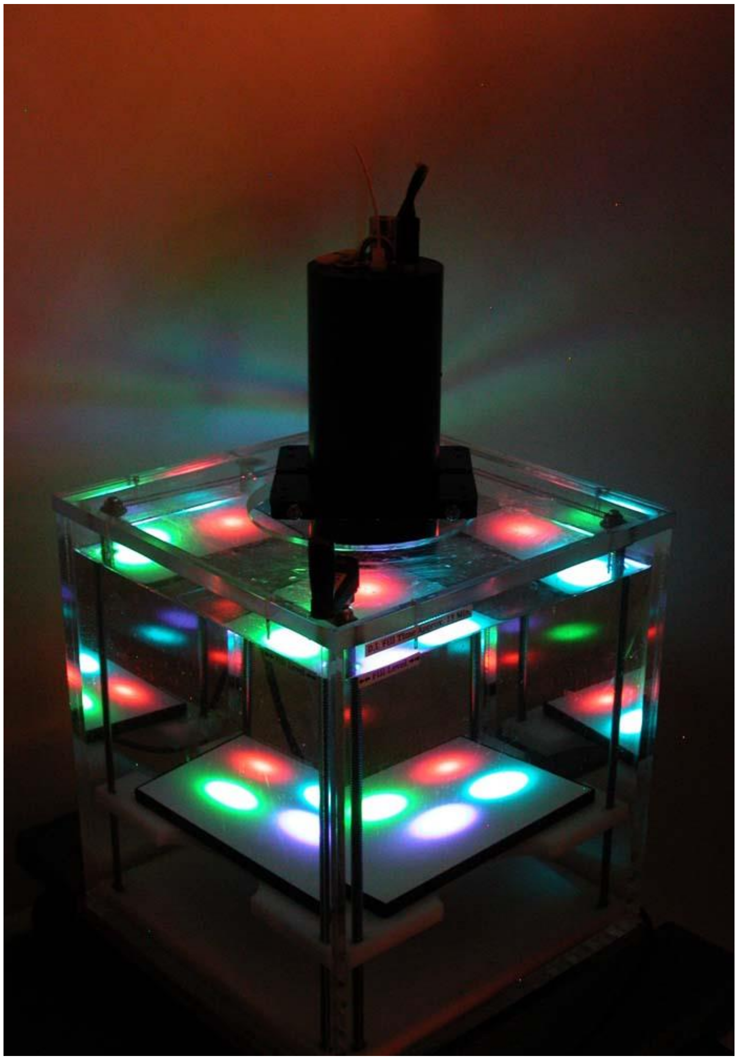
Backscattering Sensor Calibration Manual



Revision R, September, 2015

Hōbi Instrument Services

www.hobiservices.com

Revisions

Rev R, September 2015: For HydroScat-6P, simplify dark target gain procedure and recommend “Far” starting position.

Rev Q, July 2014: Formatting and editing.

Rev P, Jan 2013: Change photos to show new fixture design.

Rev O, Aug 22, 2010: Formatting; revise sections 3.4 through 3.6 to include instructions for instruments with non-flat faces (such as Series 250 HydroScat-6); correct Phot-flo dilution ratio in 2.4 from 1/100 to 1/200.

Rev N, Oct 30, 2008: Revise recommended plaque wetting procedure (2.4), add “Final Steps” section (3.8)

Rev M, May 1, 2008: Minor edits and formatting improvements. Change “target” to “plaque” in most cases.

Rev L, July 3, 2006: Add note about lubrication.

Rev K, June 15, 2006: Add note about Photo-Flo wetting agent and other notes about target maintenance (2.4)

Rev J, July 24, 2003: Add reference to washers in fixture assembly

Rev I, May 30, 2003: Add Target section (2.2) expand target maintenance section (2.4) add Coefficient Calculations section (4), include a-Beta and c-Beta in title and overview, some minor editorial changes.

Rev H December 9, 2002: HydroSoft 2.6 Changes (advanced settings, section 3.9) and new recommendation for Rho in μ calibration.

Rev G June 27, 2002: Complete revision to incorporate HydroSoft 2.5 calibration functions.

Earlier revisions not tracked

TABLE OF CONTENTS

1 OVERVIEW

HydroScats (HydroScat-2, -4 and –6), a-Beta and c-Beta are instruments for measuring optical backscattering* in natural waters. For detailed information about these instruments, see their individual User's Manuals. One of their key features is the capability for a rigorous calibration that is robust enough to be performed by users in the laboratory or in the field. The calibration requires a fixture, described in section 2, which can be purchased from Hobi Instrument Services. HydroSoft software (versions 2.5 and later) guides users through the calibration to make it as straightforward as possible.

The calibration has three primary parts: μ coefficients, dark offsets, and gain ratios, described below.

1.1 Mu coefficients

Mu (μ) is the overall coefficient of sensitivity for a channel, which allows converting its normalized electronic response to absolute backscattering. This is measured by continuously moving a target plaque with known reflectivity through a range of distances in front of the sensor. The resulting curve is integrated and weighted by known geometric factors in order to calculate μ.

The μ calibration must be executed in water.

1.2 Dark Offsets

Because of electronic factors, the instrument produces a non-zero signal even when no scattering signal is present. These offsets (which vary from channel to channel and with gain setting) are measured by blocking the face of the instrument to prevent any light from the LEDs from entering the receivers. The dark offsets are measured out of water.

The HydroScat uses the dark offset measurements internally, subtracting them in real time from the "raw" data it produces.

1.3 Gain Ratios

HydroScats have five different gain settings. These are different levels of signal amplification, which allow automatic operation in a wide variety of conditions. The lower gain settings also make possible the method of using a highly reflective plaque for the μ calibration. The ratios between adjacent gain settings are measured by recording the signal value while a channel is set to a certain gain, changing the gain by one step, and recording the new signal value.

The gain ratios can be measured either in air or in water. For convenience and the best accuracy, we recommend executing the gain calibration in air.

---

* a-Beta and c-Beta also measure attenuation; this document only applies to calibration of their backscattering measurements.

1.4 Sequence of Procedures

The three parts of the calibration, μ , dark offsets and gains, do necessarily need to be performed at the same time. The μ and dark offset measurements can be performed independently at any time. The gain calibration requires offsets to be measured at the same time.

For a complete calibration, we recommend:

1. Measure the dark offsets, outside the calibration fixture.
2. Measure the gain ratios in the calibration fixture, without water.
3. Fill the calibration fixture with water and prepare the Spectralon reflectance target, then measure the μ factors.

Note that the gain ratios should change very little over the life of the HydroScat. It should not be necessary to measure them more than once or twice per year.

1.5 HydroSoft Software

HydroSoft (version 2.72 or later recommended) guides users through the necessary calibration procedures, collects and processes the data, and stores finished calibration results. HydroSoft is also used for routine operation of the sensors, so this document presumes your familiarity with it, and discusses the details of HydroSoft that pertain strictly to calibration. For further introduction to HydroSoft and its other features, consult the HydroSoft User's Manual and also the manual for the instrument to be calibrated.

1.6 Calibration Results

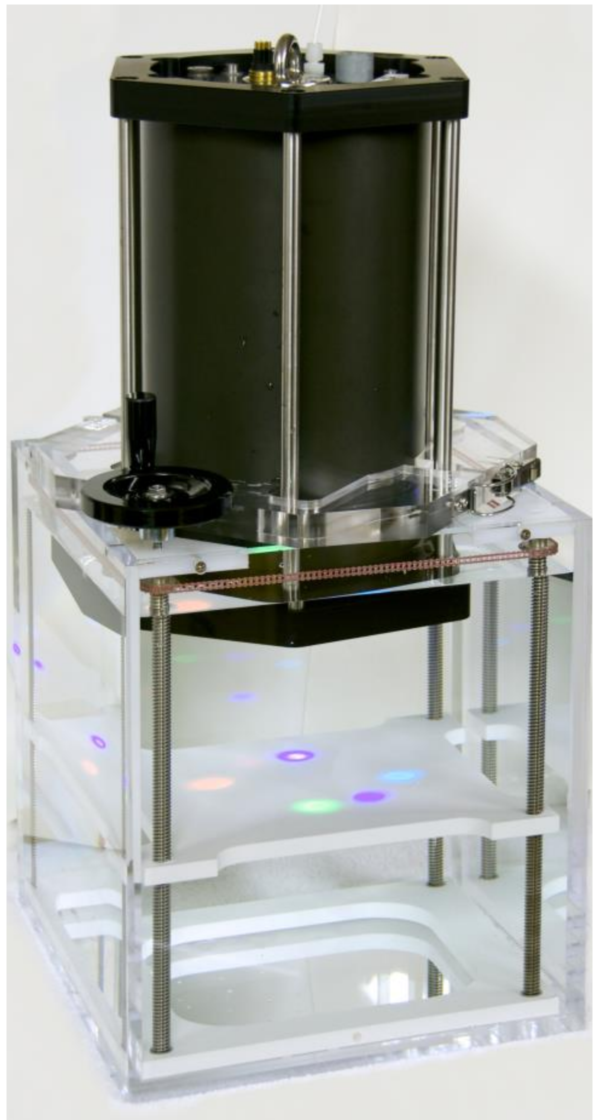
Finished calibration data are stored in structured text files on a computer, and also stored in each HydroScat's internal memory. Normally the calibration stored in the instrument is considered authoritative and is downloaded from the instrument whenever HydroSoft communicates with it. However HydroSoft can also be instructed to ignore the instrument's internal calibration and use a file instead.

2 CALIBRATION FIXTURE

2.1 Description

The standard fixture for the μ and gain ratio calibrations consists of an acrylic tank containing a platform that can be raised and lowered in precise increments. A diffuse white plaque is placed on the platform, and the tank filled with water. The instrument is placed with its face under the surface of the water, facing the plaque. The plate is then moved throughout the instrument's sensitive range according to the procedures below.

HOBI Labs built calibration fixtures of several sizes and styles. The descriptions in this document reflect the design first manufactured in 2013. This is functionally identical to the previous design shipped from 2001 to 2012, but is smaller and lighter.



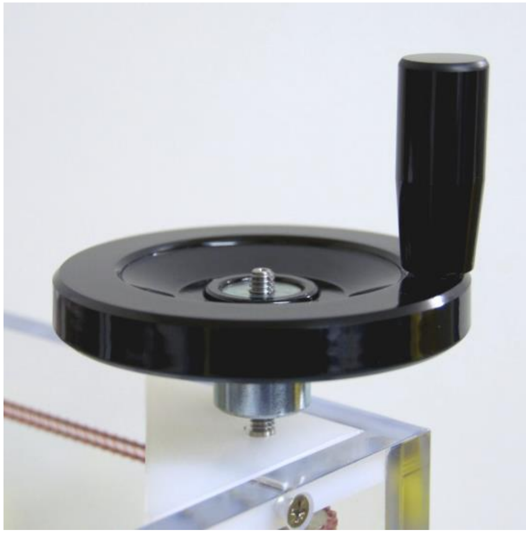
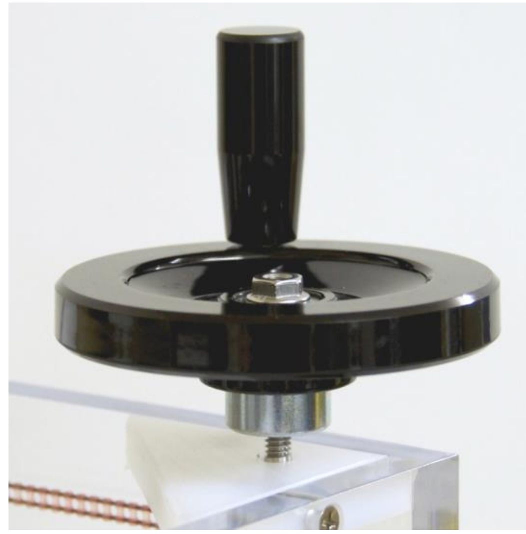
Fixture with HydroScat-6P, ready for calibration (plaque not shown). Fixtures made in 2015 and later have a hole in the platform for easier cleaning.

2.2 Handle Installation

The crank handle, used to adjust the height of the target platform, is detached from the fixture during shipment. See the installation instructions on the next page.

2.3 Calibration Plaque

The standard calibration plaque is a 10-inch square of Spectralon™, available from Labsphere, Inc., North Sutton, NH (www.labsphere.com) as part number SRT-99-100.

***Crank handle installation**: thread the handle onto the protruding rod, until about 6mm of thread protrudes above the top. Then lock it in place with the supplied nut.*

2.4 **Plaque Maintenance**

Spectralon plaques must be carefully handled and cleaned to maintain their calibrated reflectivity. They can absorb organic compounds, causing a decrease in reflectivity. Do not touch the calibrated surface with bare hands. Also see the maintenance instructions from Labsphere that come with the material.

When it is completely clean, Spectralon very effectively repels water. This means air may cling to it when it is immersed, which can seriously compromise the calibration accuracy. To determine if the plaque is properly wetted, submerge it in clean water and view the plaque from various angles. When properly wetted, it should appear uniformly white or light gray from any angle. A shiny or splotchy gray appearance indicates inadequate wetting.

To avoid this it may be necessary to rinse the plaque with a wetting agent before use. We recommend a dilute solution of Kodak Photo-Flo™ 200, which is available from suppliers of photographic equipment. Note that Photo-Flo is supplied in highly concentrated form and **must be diluted** for safe use.

The best way to wet the plaque is to prepare a 1/200 dilution of Photo-Flo 200 in a spray bottle, then spray a light layer onto the plaque. Submerge it to test whether it wets properly. Continue applying more and testing as necessary. Apply only the minimum necessary, and after submerging the wetted plaque in the calibration fixture, flow additional clean water over its surface. Wetting may also be improved by letting the plaque soak in clean water for several hours after cleaning and rinsing with the wetting solution, but do not leave the plaque in water for more than a day.

After removing the plaque from the calibration fixture, stand it up vertically in a sink or tank, rinse it thoroughly with clean water, and let it air-dry.

3 PROCEDURES

3.1 General Preparation

Computer

You will need a computer with HydroSoft 2.72 or later installed, and a COM port or USB port set up for communication with the instrument. For information on setting up and using HydroSoft, see the HydroSoft User's Manual. For the μ and gain calibrations you should locate the computer near the calibration fixture, in a position that allows you to view the screen and type on the keyboard while turning the crank handle on the fixture.

Environment

Avoid bright AC lighting, and especially fluorescent lights, during the gain calibration. On high gain settings, AC lights can cause substantial excess noise.

Calibration Fixture and Plaque

For the μ procedure, be sure the calibration fixture is clean and filled with clean water. The water need not be perfectly pure, but distilled, deionized or otherwise purified water will give the most accurate results. Check the plaque for cleanliness and for bubbles or any film of air clinging to its surface. A gray or shiny appearance indicates that the plaque is not completely wetted (see also section 2.4). It is preferable to fill the tank by placing the outlet of a hose near the bottom of the tank, under the water, to avoid generating bubbles.

Instrument Setup

Be sure that the instrument either has external power supplied, or its internal batteries have enough charge to operate it during the calibration. Do not charge a HydroScat-6 during calibration; the fast-charging circuit will interfere with data collection.

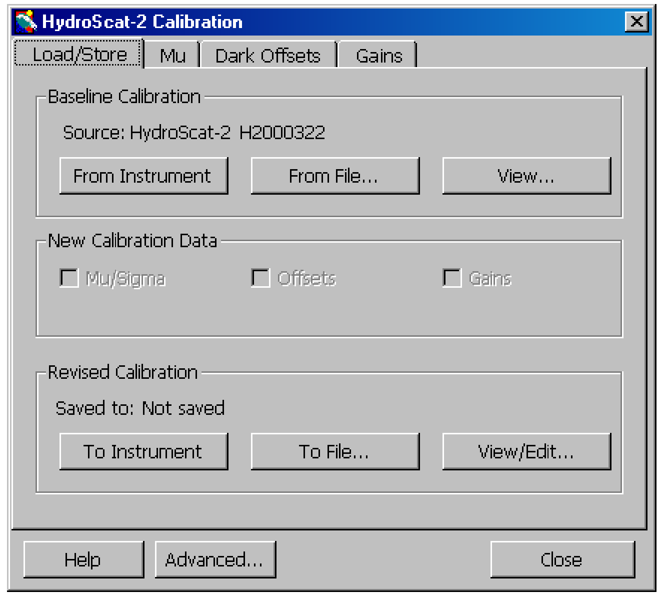
Allow the instrument to stabilize for several minutes before beginning the calibration procedure.

3.2 Startup

In HydroSoft, connect to the instrument and verify that it is communicating properly. Except in special circumstances, you should check the **Load Calibration From Instrument** option in the connection dialog box. This will ensure that the revised calibration you generate contains the correct configuration information about the instrument.

Select **Calibrate...** from the **HydroScat** menu, which will display the following dialog box. This contains four tabs that control the different calibration processes.

3.3 Baseline Calibration



HydroSoft builds new calibration files by combining newly measured data with "baseline" data from the instrument or from a file. Data that are not revised during the calibration procedures are copied directly from the baseline to the revised calibration. Baseline data include channel names, wavelengths and other aspects of the instrument configuration, so it is very important that the baseline match the instrument being calibrated. Usually the instrument's internal calibration is used as the baseline.

When you first open the Calibrate dialog box, the calibration that is in effect in the data window from which it was opened is adopted as the baseline. Therefore it is not usually necessary to explicitly select a baseline. However you can load the baseline from a file using the **From File...** button, or from the instrument's internal calibration with the **From Instrument** button. Whenever you select a new baseline, baseline data are immediately copied to the revised calibration, but they will not overwrite any new calibration data you have collected.

Clicking the **View...** button will open a window in which you can browse the contents of the baseline calibration. You can leave this window open while proceeding with the calibration, in order to compare the baseline and revised data.

3.4 Dark Offset Measurement

This procedure does not require use of the calibration fixture. It is not required for the μ calibration, but it is advisable to update it every time the μ calibration is performed. It is required whenever the gain calibration is performed.

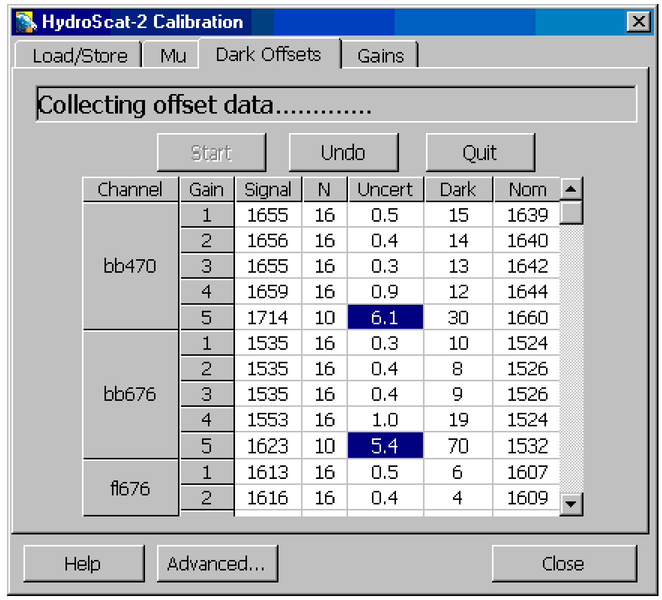
Preparation

Set the HydroScat face down on several layers of black felt or similar material, or on the black cover supplied with the instrument Be sure the HydroScat is on a flat surface and that its face is in contact with the covering material, so that no light can possibly travel between the windows.

If the HydroScat does not have a flat face, for example a HydroScat-6P in its deployment cage, use the supplied cover that presses directly against the windows.

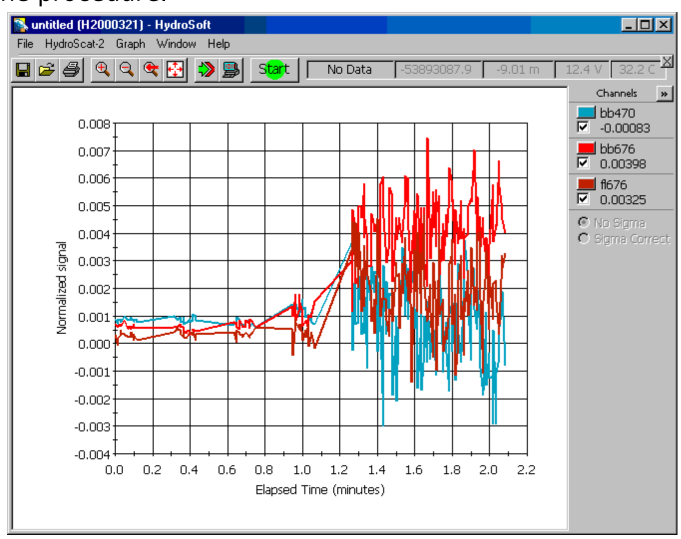
Data Collection

On the **Dark Offsets** tab of the **Calibration** window, click **Start**. HydroSoft will proceed to measure the offsets on each of the instruments channels and gains, displaying the results in a table. It will also display the raw data in the graph window. HydroSoft calculates the standard deviation of the data while it samples the offsets and continues averaging on each gain until the maximum uncertainty falls below the value entered in the **Advanced Settings** dialog box (section 3.9). While sampling, it highlights the values that exceed the uncertainty goal, as shown in the illustration.



Occasionally an outlying point or some disturbance to the setup may prevent the uncertainty goal from being met. In this case (or for any other reason) you can click the **Undo** button to back up to a previous step in the procedure.

The **Quit** button halts the offset measurements and discards all the results.



When the measurement procedure is complete, HydroSoft will ask whether you wish to save the raw data in a file. The calibration results will not be affected by whether or not you save the raw data. The saved file cannot be used to directly reproduce the results of the measurements; it is only useful for trouble-shooting.

3.5 Mu Measurement

Preparation

Clean the windows, attach the mounting collar, and place the HydroScat in the calibration tank filled with clean water. To calibrate a HydroScat-4 with an integrated anti-fouling shutter, remove the shutter blade. The face of the instrument should be fully submerged and it should be level in the tank (the face of the instrument should be parallel to the plaque). Make sure there are no bubbles on the HydroScat windows, and continue to monitor the windows during the procedure to be sure that no bubbles accumulate. Also make sure that the plaque is well saturated with water, and there are no bubbles on the plaque. If bubbles begin to accumulate in either place before the μ calibration is complete, they must be wiped away, and the calibration must be restarted.

Setting the Channel Gains

The first step in μ calibration is to determine which gain best matches each channel's sensitivity to the calibration plaque. This requires monitoring the signals while moving the plaque through the sensor's peak-response zone. To do this, click the **Start** button, then follow the on-screen instructions.

Measuring the μ Response Curves

After the gains have been properly set, HydroSoft will instruct you to move the calibration plaque ("target") to its starting position.

For instruments with flat faces, move the platform until the plaque is as close as possible to the face of the instrument without actually touching it, and leave the Start Distance set to its default value of 0 cm.

For a HydroScat-6P with its deployment frame installed, set the Start Distance to 1.3 cm and move the plaque until it almost touches the frame ring.

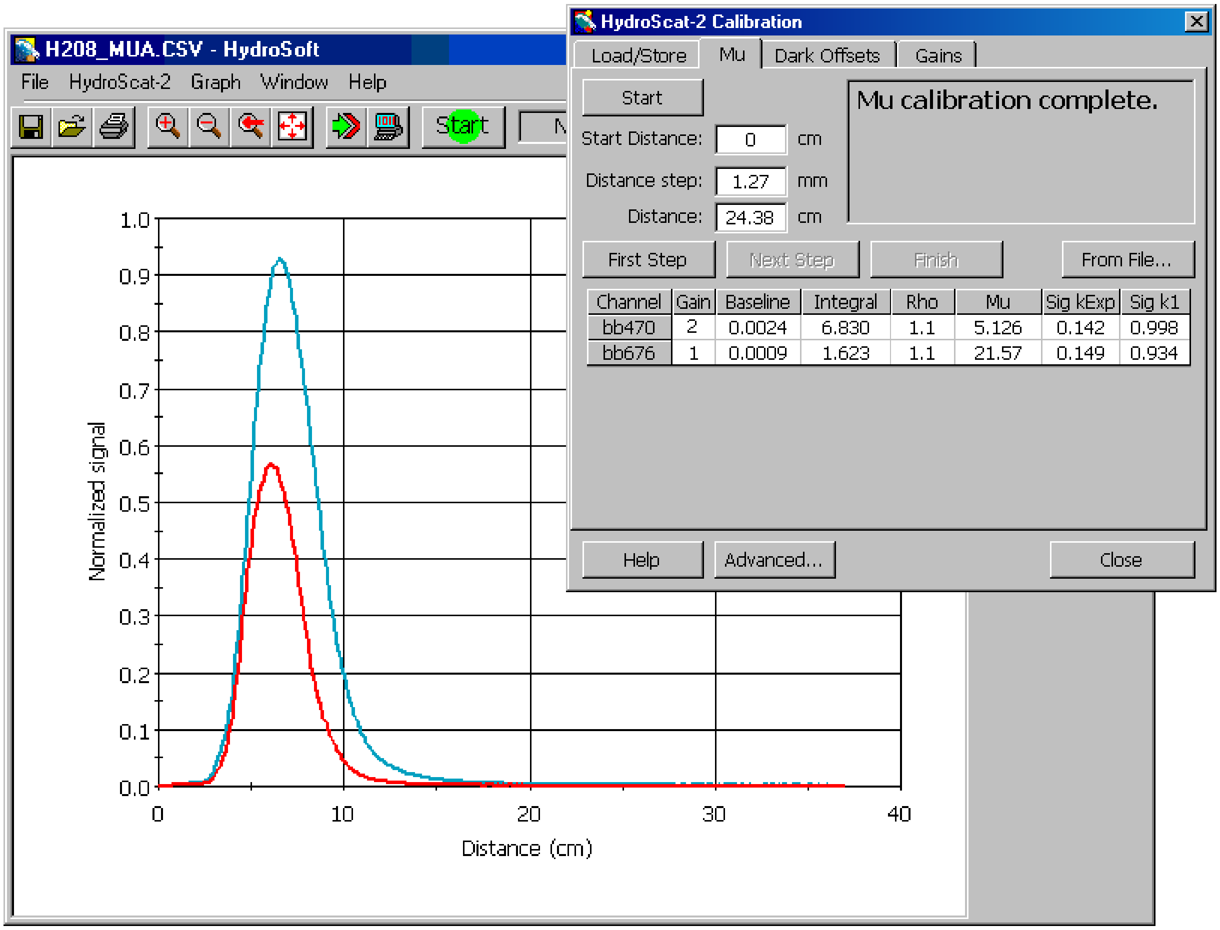
For other instruments with non-flat faces, for example a HydroScat-4 with an integrated anti-fouling shutter, measure the length of the longest protrusion for the face, and enter that value as the Start Distance.

For all instruments, confirm that the Distance Step entered in the form is appropriate, normally 1.27 mm.

When the target is set to its starting position, click the **First Step** button. HydroSoft will open a new graph in the data window, and perform some other initializations that may take a few seconds. When this process is complete, turn the crank handle one turn if your calibration fixture has 1.27 mm thread pitch (fixtures manufactured before June 2002), or ½ turn if it has 2.54 mm pitch (fixtures made since June 2002), then click **Next Step** or press the enter key. Continue, clicking **Next Step** after each turn or half-turn. HydroSoft will display the evolving curves in the data window, and automatically determine when adequate data have been collected (see section 0.0 for details). At that time it will beep, and display a message informing you that you can either continue collecting further data, or click the **Finish** button to calculate the final results and transfer them to the revised calibration.

Plaque Reflectivity

You can directly enter reflectivity values in the **Rho** column of the μ results table, either before or after collecting the data curves. The μ values will be recalculated each time you change **Rho**. For Spectralon plaques you normally use the default value of 1.10 for all channels.*



Example measurement results for a HydroScat-2

Loading a File

You can load μ curves from a previously saved file, and recalculate their μ values, by clicking the **From File...** button and selecting a suitable file.

3.6 Gain Ratio Measurement

This procedure is the most involved of the three, but because the gain values are normally extremely stable it is also not required very often. Note that the gain ratio calculations require that you also perform the dark offset calibration before saving the gain values.

---

* The Rho value of 1.10 was introduced in December, 2002. In previous HydroSoft versions the default value was 0.98, based on irradiance reflectivity measurements provided by Labsphere. HOBI Labs revised this based on careful measurements of the *radiance* reflectivity, in water and at angles appropriate to the HydroScat measurement geometry.

Setup

It is usually most convenient to perform this procedure in the same fixture as the μ calibration. However the target can be any object that can be set to stable positions, and the measurements need not be done in water. If you use water, beware of bubbles or particles that might move during the measurements.

This procedure should be performed in subdued lighting, preferably with no fluorescent lights, to avoid excessive noise when measuring the higher gains. However the room need not be completely dark.

Basic Procedure

To measure the gain ratios, you move the target to a position that causes a near-peak response from one or more channels on a particular gain setting. Then, while the target remains stationary, HydroSoft measures the response to the target on the current gain, reduces the gain one step, then measures the response again. This is repeated until all gain ratios have been measured for each channel of the instrument.

Direction of Motion

At the beginning of the gain calibration procedure, HydroSoft offers a choice of whether to start the target near the instrument face, and gradually move it away during the procedure, or to start with it far and bring it gradually closer. The choice varies depending on the version of HydroScat and version of the calibration fixture you are using.

For HydroScats with flat faces, which can be placed within a few mm of the calibration target, it is preferable to select the **Near** option. For HydroScat-6P instruments in their deployment cages, it is typically better, and sometimes necessary, to use the **Far** option in connection with the "dark" target, as explained below.

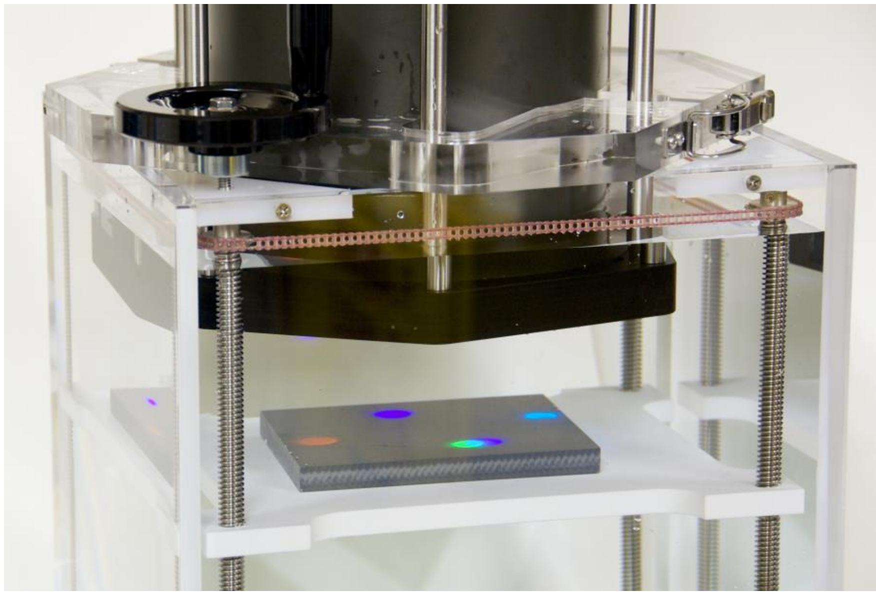
Setup and Procedure for HydroScat-6P

Gain calibration of the HydroScat-6P requires a gray ("dark") target in order to provide the correct signal levels. Previous versions of this document recommended a two-step process in which the dark target was used for only part of the procedure. The following procedure is simpler, but equally effective.

Place the dark target on the platform of the calibration fixture, centered under the instrument. Move the target platform to the bottom of the fixture. Then begin the standard gain procedure, selecting the **Far** option for the direction of motion.

Setup and Procedure for Other Instruments

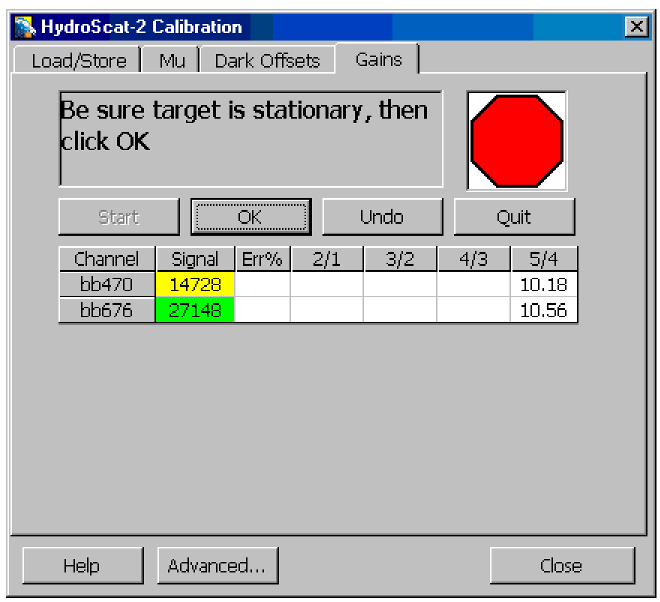
For instruments whose configurations allow this, place the white plaque on the calibration platform, and move it to approximately 1mm from the face of the instrument. Select the **Near** option for the direction of motion.



Dark target for gain calibration of HydroScat-6P

Continuing Procedure

Once you have selected the direction of target motion, HydroSoft continuously monitors the signal levels from the instrument and instructs you when and in which direction to move the target. During this process it highlights the numerical signal values with colors to indicate how close they are to their ideal values.



GREEN highlighting indicates values in the optimum range. When at least one channel is in this range, HydroSoft will instruct you to stop the target, and when you acknowledge this it will proceed to measure ratios on the eligible channels. Eligible channels include those in the acceptable range, which are shown with YELLOW highlighting. RED indicates a channel is saturated. In this case HydroSoft will instruct you to move the target in the appropriate direction to reduce the signal. WHITE (no highlighting) indicates a channel is either below the minimum acceptable value, or that it is not presently being considered for measurement regardless of its value. This can happen if the channel has already been measured on the current gain, or if hardware limitations prevent it from being measured simultaneously with some other channel.

When the gain measurement procedure is complete, HydroSoft will ask whether you wish to save the raw data in a file. As with the offset measurements, this is offered strictly as a backup in case troubleshooting is required. The calibration results will not be affected by whether or not you save the raw data.

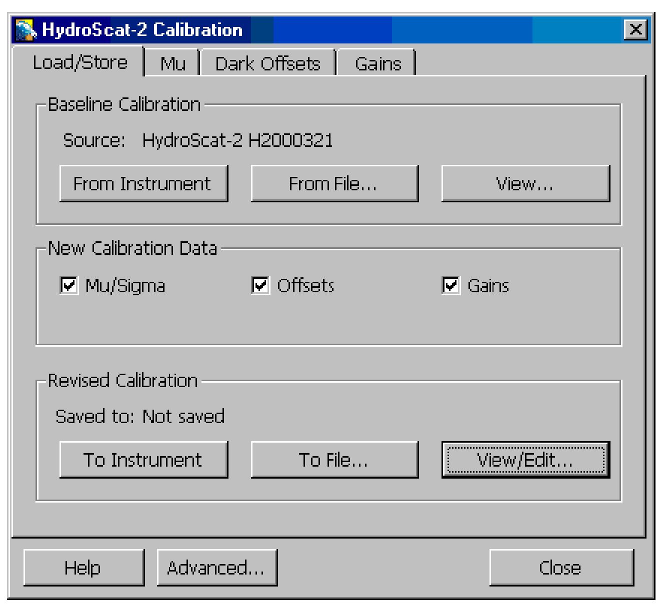
3.7 Storing Calibration Results

When you complete each calibration procedure, the corresponding check box under **New Calibration Data** on the **Load/Store** tab will become checked and enabled. This indicates that the newly-measured values have been copied into the revised calibration. You can uncheck them if you decide not to use the new data, or if you wish to compare the new and old values in the **Revised Calibration** window (opened by clicking on the **View/Edit...** button). If you leave this window open while checking or unchecking the new calibration options, you will see the values change immediately to reflect your selections. You can also compare the values side-by-side by opening both the **Baseline Calibration** and **Revised Calibration** windows.

In the **Revised Calibration** window you can click on the lock icon to enable direct editing of most of the calibration values.

Once you are satisfied with your calibration results, you can save them in the instrument's memory, in a file, or both. When you click the To Instrument button, HydroSoft will transmit the complete calibration to the instrument, check to verify that it was correctly received, and if so ask whether you wish to save it in the instrument's nonvolatile memory. If you choose not to, the calibration you just loaded will remain in effect until the next time the instrument is reset. A reset can be caused by a loss of power (including use of the "battery disconnect" function of battery-powered HydroScats), by an explicit reset command sent to the instrument, or by the **Reset** command on HydroSoft's **Instrument** or **HydroScat** menu.

If your baseline calibration was loaded from the instrument and you subsequently save a revised calibration to the instrument, the baseline retains its former values until you explicitly reload the calibration from the instrument. If you reload the calibration you will no longer be able to compare the old baseline with the new values.



3.8 Final Steps

When you are completely finished with the calibration, you should close the **Calibration** dialog box before disconnecting the instrument or putting it to sleep. During the calibration process HydroSoft changes some settings of the instrument, and it sends commands to restore these settings at the time the dialog box is closed.

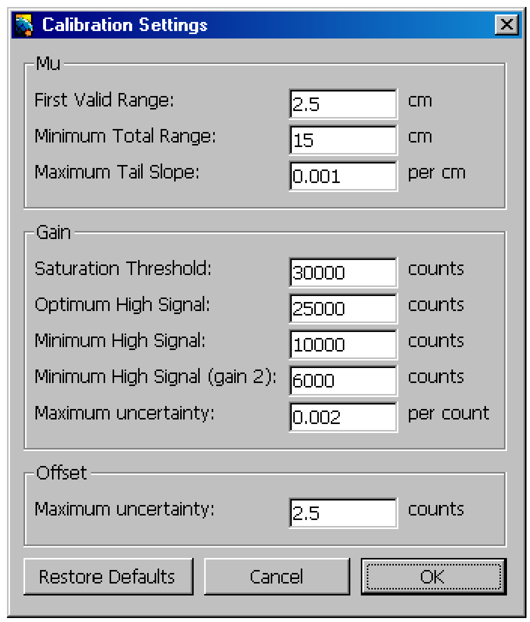
NOTE: HydroSoft does not automatically adopt the new calibration into its existing data windows. That is, if you collect new data from your instrument after completing the calibration, HydroSoft will still display it with the old calibration values unless you explicitly load the new calibration from a file, or from the instrument (by reconnecting to it).

3.9 Advanced Settings

If you click the Advanced.... button (new in version 2.6) in the calibration dialog box, the following dialog will appear and allow you to control parameters of the calibration process. In most cases you should leave these set to their defaults.

Mu (μ)

During the calculation of μ, only data collected at ranges greater than or equal to the **First Valid Range** will be included in the calculation. This is independent of the **Starting Distance** you set on the μ tab of the main calibration dialog. The **Starting Distance** informs HydroSoft of the actual distance at the beginning of the calibration, whereas the **First Valid Range** controls what range of data will actually be included in the calculation. This setting is required because signals at shorter ranges are dominated by multiple reflections between the instrument face and the calibration target, and the actual backscattering signals are negligible.



Minimum Total Range and **Maximum Tail Slope** determine the total range of data that HydroSoft will require for a μ calculation. HydroSoft will only calculate μ if the range of data included is at least equal to **Minimum Total Range**. It also requires that the slope of the curve's "tail" is below the **Maximum Tail Slope**. A low tail slope indicates that no further information would be gained by measuring at larger ranges. For example the default value of 0.001 means that each additional cm of range would change the μ value less than 0.1%.

Gain

The first four gain parameters control how HydroSoft determines the signal levels it will require for measuring gain ratios. As described in section 3.6, the program will direct the user to adjust the target distance until at least one of the channels is above **Optimum High Signal** but below **Saturation Threshold**. Then it will measure the gain for that channel and any others that are between **Minimum High Signal** and **Saturation Threshold**. A different **Mini-**

mum High Signal is set for gain 2, because some instruments do not have enough overall gain to reach the regular threshold on that gain.

When collecting gain ratio data, HydroSoft collects as many samples as are required to bring the sample uncertainty below **Maximum Uncertainty**. Raising this value decreases the amount of time it takes HydroSoft to measure the gain ratios, but increases the possible error.

Offset

When measuring dark offsets, HydroSoft calculates the statistical uncertainty of the samples it has collected, and continues until the uncertainty falls below the value specified here. Some individual instruments have higher noise levels than others and therefore require more samples to achieve this uncertainty. In extreme cases the uncertainty may never fall below the threshold, in which case the threshold can be raised here.

4 COEFFICIENT CALCULATIONS

The following is a brief presentation of the key equations used to calculate calibration coefficients during the above procedures. For a complete description of the theory and mathematics behind the calibration, see “Instruments and Methods for Measuring the Backward-Scattering Coefficient of Ocean Waters”, by Robert A Maffione and David R. Dana, *Applied Optics* Vol. 36, No. 24, 20 August 1997.

4.1 **Mu**

$$\mu = \frac{\rho_L}{\pi \sum_{z_{min}}^{z_{max}} \frac{S_n(z) - S_n(z_{max})}{\cos\left(\tan^{-1}\left(\frac{H}{2z}\right)\right)} \Delta z}$$

$$S_n = \frac{S - S_{off}}{R - R_{off}}$$

S is the raw signal from the instrument, in digital counts, measured when the LED is on,

S_{off} is the raw signal when the LED is off (the signal due to electronic offsets)

R is the reference measurement of LED output when the LED is on,

R_{off} is the reference measurement when the LED is off (due to electronic offsets),

z is the distance from the instrument face to the calibration plaque,

H is the distance between the centers of the source beam and receiver field of view (depends on the instrument model),

ρ_L is the radiance reflectivity of the calibration plaque.

z_{min} is the minimum distance to consider in the calibration; at very small values of z, the only light received is due to multiple reflections between the plaque and the instrument face, which should not be included in the measurement.

z_{max} is the distance beyond which the plaque is invisible to the sensor.

Note that ρ_L differs from the irradiance reflectance normally reported for Spectralon, which is 0.99 in air. The irradiance reflectivity is the ratio of the total reflected flux to the total incident flux, and cannot have a value greater than 1. On the other hand, the radiance reflectance, the ratio of reflected radiance to incident irradiance, varies as a function of angle. A perfect Lambertian reflector would have radiance reflectivity of 1 at all angles, but realistic reflectors may have values greater than 1 at some angles, indicating a specular reflection component. In this case, conservation of energy demands that that the reflectivity be less than 1 at other angles.

HOBI Labs' measurements of Spectralon reflectivity in water show that with incident irradiance at 20 degrees from normal (as for the HydroScats), its radiance reflectivity at 20 degrees reflected angle is 1.10.

4.2 Sigma

Before scattered light is measured by the backscattering sensor, it must travel from the sensor to the scattering site and back. Over that distance some light will be lost to the water's attenuation, resulting in an underestimate of scattering. For clear waters this is insignificant, but as turbidity increases so does the underestimate of scattering. To compensate for this, calibrated backscattering values are multiplied by the function $\sigma(K_{bb})$. $\sigma(K_{bb})$ has a value of unity for very clear water, and increases as attenuation, characterized by the coefficient K_{bb}, increases.

The response function collected in order to calculate μ, that is, $S_n(z)$, is also used to derive $\sigma(K_{bb})$, which is define as follows.

$$\sigma(K_{bb}) = \frac{\int_0^\infty W(K_{bbw}, z)\, dz}{\int_0^\infty W(K_{bb}, z)\, dz}$$

where

K_{bbw} is K_{bb} of the water in which the sensor was calibrated, and

$$W(K_{bbw}, z) = \frac{S_n(z) - S_n(z_{max})}{\cos(\tan^{-1}(H/2z))}$$

It can also be shown that having measured $W(K_{bbw}, z)$ during the calibration procedure, one can then calculate, for any K_{bb},

$$W(K_{bb}, z) = W(K_{bbw}, z)\exp\big((K_{bbw} - K_{bb})(r_s + r_r)\big)$$

where

r_s is the distance along a line from the center of the source beam to the center of the scattering site,

r_r is the distance along the return path to the receiver.

Using these relationships, HydroSoft can then calculate

$$\sigma(K_{bb}) = \frac{\sum_{Z_{min}}^{Z_{max}} W(K_{bbw}, z)\Delta z}{\sum_{Z_{min}}^{Z_{max}} W(K_{bb}, z)\Delta z}$$

However, to enable a much more efficient calculation of $\sigma(K_{bb})$ during processing of in-situ data, as well as to minimize the amount of information that must be contained in an instrument's calibration file, we desire to simplify the above expression. Because of the exponential relationship between and $W(K_{bb}, z)$, $\sigma(K_{bb})$ can be closely approximated by

$$\sigma(K_{bb}) \cong k_0 \exp(K_{bb} k_{exp})$$

where

$$k_{exp} = \frac{\ln \sigma(K_{bbw} + 3)}{K_{bbw} + 3}$$

and

$$k_0 = \exp(-k_{exp} K_{bbw})$$

For these coefficients, HydroSoft calculates K_{bb} by assuming the calibration water has absorption equal to that of pure water, and scattering equal to twice that of pure water. While these are obviously crude assumptions, their effect on the outcome of the computation is very small, unless very poor-quality water is used during the calibration.

The value of 3 used in the above expression for k_{exp} was determined empirically to provide very accurate fitting of $\sigma(K_{bb})$ for K_{bb} values from 0 to 10.

4.3 Dark Offsets

$S_D(g)$ is the residual signal measured on gain *g* (where *g* designates one of five possible gain settings), when there is no actual backscattering signal present. It is calculated (for every gain on every channel) by $S_D(g) = S - S_0$ (see the variable definitions above).

4.4 Gains

Each backscattering channel has five discrete gain settings that adjust its sensitivity over a five decade range. They are measured by adjusting the distance to a reflective target until the sensor's response is near its maximum; then the gain is reduced by one step and the response to the same target measured on the lower gain. This allows calculating the ratio of the two gains from

$$R_g = \frac{G_g}{G_{g-1}} = \frac{S(g) - S_D(g)}{S(g-1) - S_D(g-1)}.$$

Once all four ratios are known, the specific *G* values are determined by defining *Gg* as 1 for the setting *g* in effect when *μ* is measured (*g* = 1 or 2). That is, if *μ* was measured on gain 1,

$G_1 = 1$

$G_2 = R_2$

$G_3 = R_2R_3$

$G_4 = R_2R_3R_4$

$G_5 = R_2R_3R_4R_5$

If *μ* was measured on gain 2,

$G_1 = 1/R_2$

$G_2 = 1$

$G_3 = R_3$

$G_4 = R_3R_4$

$G_5 = R_3R_4R_5.$