Appendix B. Principles of Operation

This document introduces the operating principles of the SonTek-SL Doppler current meters. It does not attempt to provide a detailed discussion of all technical issues, nor does it provide a detailed description of SonTek-SL products operation. To learn more about specific SonTek-SL applications, please refer to other sections of the *SonTek-SL User's Manual* or contact SonTek Support.

Overview

SonTek-SL products are Doppler current meters designed for water velocity, level, and flow measurements in the field. The SonTek-SL product line provides the technological advantages of complex/expensive current profilers, but in a simple, inexpensive, and easy to use package. SonTek-SL products attributes include:

- Horizontally integrated velocity measurement
- Measurements to the maximum possible extent of the water column
- Invariant factory calibration — no periodic recalibration required
- Simple operation (very few user entries needed)
- Excellent performance for low and high flows
- Accuracy — 1% of measured velocity
- Water level measured by vertical beam and pressure sensor
- Built-in temperature sensor

Typical applications for the SL include:

- River discharge monitoring
- Velocity indexing
- Irrigation
- Flood alert systems
- Water supply
- Environmental monitoring
- Vessel traffic
- Offshore platforms
- Ship berthing

The Doppler Shift

The SL measures water velocity using a physical principle called the Doppler shift. This principle states that if a source of sound is moving relative to the receiver, the frequency of the sound at the receiver is shifted from the transmit frequency. For a Doppler current meter, this can be expressed as:

$$F_d = -2F_0 \frac{V}{C}$$

where

F_d = Change in received frequency (Doppler shift)
F_0 = Frequency of transmitted sound
V = Represents relative velocity between source and receiver (i.e., motion that changes the distance between the two); +V means the distance from source to receiver is increasing.
C = Speed of sound

The SL is a *monostatic* Doppler current meter. Figure 86 illustrates the operation of a monostatic Doppler current meter.

- Monostatic means the same transducer is used as transmitter and receiver.
- The transducer generates a short pulse of sound at a known frequency (F_0), which then propagates through the water.
- The transducer is constructed to generate a narrow beam of sound where the majority of energy is concentrated in a cone a few degrees wide.
- As the sound travels through the water, it is reflected in all directions by particulate matter (i.e., sediment, biological matter, bubbles).
- Some of the reflected energy travels back along the transducer axis, where the transducer receives it.
- The SL electronics measure the change in frequency of the received signal.
- The Doppler shift measured by a single transducer relates to the velocity of the water along the axis of the acoustic beam of that transducer.
- If the distance between the transducer and the target is decreasing, frequency (F_D) increases; if the distance is increasing, frequency (F_D) decreases. Motion perpendicular to the line-connecting source and receiver has no effect on the frequency of received sound.

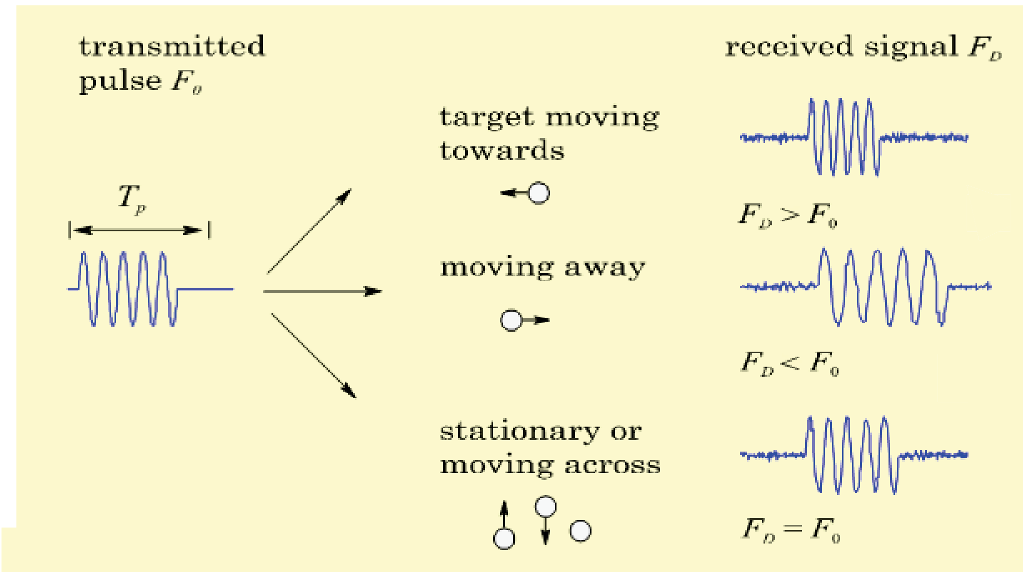

Figure 86. Measuring target velocity with a monostatic Doppler system

The location of measurements made by a monostatic Doppler current meter is a function of the time at which the return signal is sampled.

- The time since the pulse was transmitted determines how far the pulse has propagated, and thus specifies the location of the particles that are the source of the reflected signal.
- By measuring the return signal at different times following the transmit pulse (T_P), the SL measures the water velocity at different distances from the transducer.
- It is important to note that the SL measures the velocity of particles in the water, and not the velocity of the water itself.
- The velocity of particles in the water is assumed to match the velocity of the water. This assumption has been tested extensively and found to be highly reliable.
- If there is no particulate matter in the water, the SL is unable to measure velocity. In general, the practical limitation of clear water is not whether the SL can make velocity meas-

urements, but what is the maximum range (distance from the system) at which the SL can measure velocity. In clear water, the maximum measurement range may be reduced.

Important Note: *Clear water* is a relative term; visual inspection is not a good way to determine particulate matter concentration. Beam Check, in the Utilities Tab of the SL software can be used to make an on-site field determination of range.

Beam Geometry

The SL is designed for horizontal operation from underwater structures such as bridge pilings and channel walls.

- The system measures velocity in a horizontal layer (parallel to the water surface) away from the flow interference generated by the structure.
- The system uses two acoustic velocity beams in a single plane, each slanted 25° off the instrument axis. This beam geometry is designed for side-looking applications, giving the optimal balance between 2D velocity response and total measurement range (Figure 87).
- The velocity measured by each beam is referred to as the *along-beam velocity*.
- Beam velocities are converted to XY (Cartesian) velocities using the beam geometry.
- In most applications, the orientation of the SL is known and XY velocities are used directly.
  - XY velocities are reported relative to the orientation of the SL; if the SL is looking across a stream, X is parallel to the direction of flow and Y is across the stream.
- SL systems include a vertical beam to measure the distance from the top of the system to the water surface.

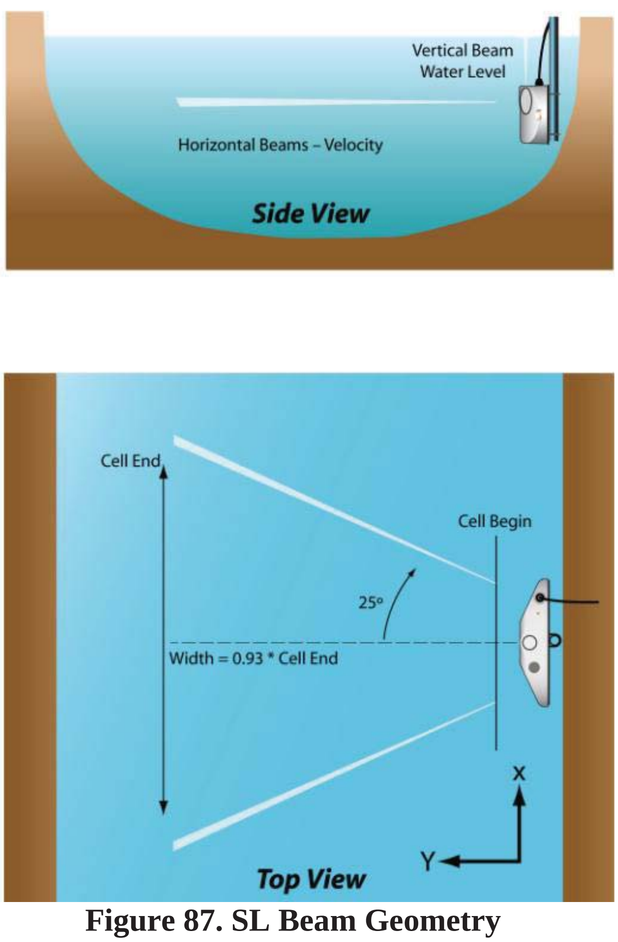

Figure 87. SL Beam Geometry

Water Level Measurement

Water level (Stage) is determined by using a vertical beam and integrated pressure sensor.

- The vertical beam sends a short sound pulse and listens for the reflection from the surface.
- The surface reflection is very strong and clearly defined, allowing SonTek-SL products to precisely measure the time at which the return reflection is received.
- To convert the reflection time to surface range, SonTek-SL products needs to know the speed of sound in the water at the site, which is primarily a function of temperature and salinity.
    - Th SLs have an internal temperature sensor that automatically compensates for changing conditions by continually updating the sound speed used for surface range calculations.
    - Salinity is user defined. SonTek-SL products do not automatically adjust for salinity variations.
- The vertical beam operating range depends on the SL system frequency. The range specifications can be found in Appendix D.
- The vertical beam works in conjunction with the integrated pressure sensor to determine water level
    - The vertical beam is the principle measurement
    - The pressure sensor is used as a secondary measurement in the case that there is no valid data from the vertical beam
- The pressure sensor is not vented to the atmosphere thus it must be calibrated for changes in atmospheric conditions.
    - The pressure sensor is calibrated during the deployment using data from the vertical beam. Thus both sensors can provide reliable and accurate water level data.
- Water level data are used to modify the measurement volume location in real-time, optimizing performance with changing water level.

Flow Calculations

One of the primary functions of the SonTek-SL products is to provide real-time flow data and total volume data for water deliveries. SonTek-SL products combine water velocity data and level data with user-supplied channel geometry information about the installation site to calculate flow and volume. SonTek-SL products support flow calculations for a variety of environments:

- Natural streams (defined by a series of survey points)
- Regular and irregular (trapezoidal) channels (typically concrete lined)
- Regular (trapezoidal) culverts with a closed top
- Any channel that can be represented with a stage/area equation

SonTek-SL products combine channel geometry with stage to calculate the cross-sectional area. The area is then multiplied by the mean channel velocity to determine flow. The relationship between the velocity measured by SonTek-SL products and the mean channel velocity can be determined two ways:

- Theoretical flow calculations
- Index velocity calibration

SonTek-SL products can use the measured flow rate to compute the total volume. Total volume is the cumulative sum of flow rate multiplied by time. An example of this type of data is total irrigation volume. This the amount of water delivered through an irrigation channel over a given time span. Total volume is available both in real-time display and output, as well as in the recorded data.

Theoretical Flow Calculations

Theoretical flow calculations are used when no reference flow data are available; that is, only channel geometry and data measured directly by the SL are available. For theoretical flow calculations, the SL makes use of the following information.

- The largest variations of velocity occur with changing depth within the channel.
- Based on the supplied channel geometry, the SL can determine the vertical location of the velocity measurement within the water column. The system assumes the river follows a power-law velocity profile model with a 1/6 power-law coefficient.
- Using this model, combined with the location of the SL velocity measurement, the SL estimates a relationship between the measured velocity and the mean channel velocity.
- The relationship between measured and mean channel velocity will change as water depth changes, since the location of the SL measurements within the water column is also changing.
- The theoretical velocity calculation of the SL should provide good results for regular, concrete lined channels (typically rectangular or trapezoidal in shape) where the SL is installed near the midpoint of the water depth.
- For natural streams or sites with large variations in water depth, SonTek recommends developing an index velocity calibration to provide accurate flow data specific to that site.

Index Velocity Calibration

An index velocity calibration is a popular technique for monitoring discharge when reference discharge measurements are available.

- Discharge measurements are made at a variety of water levels and flow conditions.
- SL water velocity data and stage data are collected at the same time as reference discharge measurements.
- These data are analyzed to determine an empirical relationship between the SL measured velocity and the mean channel velocity. This empirical relationship is then input into the SL, which outputs calibrated flow data in real time.
- The empirical index relationship uses the following form:

$$V_{mean} = V_{intercept} + V_{meas} * (V_{slope} + (StageCoef * Stage))$$

where:

V_{mean} = mean velocity in the channel
$V_{intercept}$ = user-supplied* velocity offset (cm/s or ft/s)
V_{meas} = SL measured velocity
V_{slope} = user-supplied* velocity scale factor (no units)
StageCoef = user-supplied* water depth coefficient (1/s)
Stage = measured stage (total water depth) (m or ft)

***Important**: These constants are empirically derived coefficients based on several user-made, independent discharge measurements. These coefficients relate SL product measured velocity to mean channel velocity as determined by the independent measurements. The details of how these constants are derived are beyond the scope of this appendix. For more information, contact SonTek.

An index velocity calibration will usually supply more accurate flow data than a theoretical flow calculation. However, an index calibration requires extensive reference data and data analysis expertise to construct — for many applications, this is not practical. In these situations, the theoretical flow calculations can provide good quality flow data.

SonTek-SL Data

Sampling Strategy

The SonTek-SL products average data for a fixed interval for each reported water velocity sample.

- The SL samples velocity (via ping) each second. The type of velocity pings depends upon flow conditions.
- The SL pings the vertical beam once per second to measure stage data.
- Pings are accumulated over a user-specified sample duration (typically 1 to 15 minutes) and average values for velocity, stage, and a variety of diagnostic data are reported.
- The sampled data are normally recorded to the SL's internal recorder, and can also be reported to an external data logger.
- The SL can operate continuously (i.e., start the next sample immediately after completing a sample), or it can enter a low power (i.e., sleep) state between samples to conserve power.

Velocity Data

The SL velocity data are determined using three types of acoustic pulses. The SL automatically determines the best pulse scheme to provide the best possible velocity data.

- The SL can measure water velocities from ±0.001 to 7 m/s.
- The SL also measures flow direction and will accurately report reversing flow.
- Data are output in Cartesian coordinates (XY) relative to system orientation.
- Velocity data are accurate to 1% of the measured velocity (after accounting for random noise).
- The SL provides diagnostic parameters with each sample to verify the quality and accuracy of these data.
- The SL calibration will not change with time; the system never requires re-calibration.

Accuracy of Velocity data

The SL is well suited to low-flow applications to less than 0.01 m/s. When discussing the accuracy of the SL water velocity data, we are referring to the presence of any bias in mean velocity measurements. Velocity data may have random short-term variations (noise) that do not reflect a bias to velocity data. Two factors influence the accuracy of SL velocity data: sound speed and beam geometry.

- With properly specified salinity data, sound speed errors are negligible (less than 0.25%).
- Beam geometry is fixed during system construction and will not change with time (unless there is catastrophic physical damage to the system).
- The SL calibration is specified to 1.0% of the measured velocity.
- There is no potential for zero offset or drift in velocity measurements and no inherent minimum measurable velocity.

Signal-to-Noise Ratio
The SL measures velocity by looking at the reflections of an acoustic pulse from particles in the water.

- The magnitude of the reflection is called signal strength. It varies with the amount and type of suspended material, and with the distance from the transducers.
- Signal strength decreases with distance from the transducer due to geometric spreading and sound absorption.
- The distance at which signal strength approaches the electronics noise level determines the maximum measurement range of the SL.
- Signal strength is commonly used as the signal-to-noise ratio (SNR), which compares the magnitude of the received signal to the ambient electronics noise level.
- SNR is reported in logarithmic scale.
- Signal strength data are measured and recorded in internal logarithmic units called counts.
    - Signal strength and noise level are recorded in counts; one count equals 0.43 dB.
    - Signal strength is converted to SNR by subtracting the noise level and converting to dB.
- The SL requires a minimum SNR (≈3 dB) to make accurate velocity measurements.

- Signal strength and SNR reported are the mean value over the measurement volume.

- Signal strength decreases with range from the transducers and will vary with conditions in the water. For good operating conditions, SNR should be greater than 3 dB.

When SmartPulse is enabled, the SL will automatically change the horizontal range of the measurement based on water depth.

- In most conditions, the SL is able to measure to the specified maximum range of 5 m for the SL3000 and 20 m for the SL1500.

- If at any point the signal strength is too low for reliable velocity measurements, the SL will end the measurement volume at that range. In this situation, the system will automatically cut off the measurement volume at the maximum effective range. The exact limits of the measurement volume are recorded with each sample.

Signal strength is primarily a function of the amount and type of particulate matter in the water. While signal strength cannot be immediately converted to sediment concentration, it provides an excellent qualitative picture of sediment fluctuations and, with proper calibration, can be used to estimate sediment concentration.

Flow Data

With each sample, the SL records cross-sectional area and flow.

- Cross-sectional area depends on the user-supplied channel geometry and water level determined by the vertical beam and pressure sensor.
- Typically, the accuracy of area data is most strongly influenced by the accuracy of channel geometry, rather than uncertainty in stage data.

The SL can also be programmed to calculate total volume in addition to flow rate.

- Total volume is the cumulative sum of flow rate multiplied by elapsed time, and represents the total volume of water than has passed the SL.
- Total volume can be accumulated continuously between files (when data collection is interrupted and restarted) or reset with each data file. Several methods are also provided to reset total volume (restart the accumulation at zero) within a data file, if required.
- Total volume can be output in a variety of different units as required by the user.

The accuracy of flow data depends on a few factors.

- Accuracy of cross-sectional area
- Accuracy of velocity data
- Method used to relate measured velocity to mean channel velocity

In general, the largest factor in determining the accuracy of flow data is the method used to relate measured velocity to mean velocity. Some guidelines are presented below:

- A well-established index calibration can give real-time flow accuracy of about 2-3% of the measured flow.
- Theoretical flow calculations in a regular channel (i.e., trapezoidal, concrete lined) may give accuracy of about 3-5%. This can be strongly affected by nearby intake or outlet structures or by nearby changes in channel geometry (including bends in the channel).
- Theoretical flow calculations in natural streams can be difficult. They can provide reasonable results in streams with a simple, uniform cross section, but are notably limited in wide, shallow streams where velocity can vary dramatically across the width of the stream.

Data Output

The SL offers several options for data output, including SDI-12, Modbus, RS232 ASCII and 4-20 mA outputs.

- Only one output type (RS232, SDI-12, Modbus, analog outputs) can be used at a time.
- The SDI-12 serial bus can be used to output a portion of the SL sample data, including velocity and limited diagnostic data. Multi-cell velocity data can also be output in real-time using SDI-12.
    - For SDI-12 operation, the SL is programmed using the RS-232 serial bus, and then Connected to an SDI-12 datalogger.
    - The SL’s SDI-12 interface is compatible with SDI-12 revisions 1.0, 1.1, 1.2, and 1.3. Options are provided to allow integration with a variety of data logger types.
    - When using SDI-12, the external data logger controls the timing of SL’s data collection.

  - Sample duration must be configured for the SL to provide accurate battery life calculations when using SDI-12.
- The Modbus protocol provides a standardized means to acquire reliable digital data from a variety of sensors.
- The SL can optionally be set up to generate analog output signals.
  - The SL can generate up to four analog output signals at the same time.
  - Analog outputs can be either 4-20 mA or 0-5 VDC (only one analog output type can be used on a single system at any given time).
  - An external analog converter and special software are required to generate the analog output signals.
  - Each analog output signal can represent one variable.
  - The user specifies the range of values represented by the analog output signal, customizing the output range to the particular environment.

The SL can record data to the internal recorder at the same time as any of the above data outputs are being used. SonTek encourages users to always record (and regularly download and archive) data on the internal recorder to ensure full access to diagnostic data.

Speed of Sound Calculations

The SL uses sound speed to convert Doppler shift to water velocity. This section describes how to correct SL velocity data for errors in the sound speed used for data collection.

- Since the SL uses an internal temperature sensor for automatic sound speed compensation, user corrections are rarely needed.
- The only time sound speed corrections are normally required is if salinity has been incorrectly specified.

In shallow water, speed of sound is a function of temperature and salinity. Generally, a temperature change of 5^oC or a salinity change of 12 parts per thousand (ppt) results in a change in sound speed of one percent. The full range of typical temperature and salinity levels (from -5 to 60^oC and 0-60 ppt) gives a sound speed range of 1375-1600 m/s (total change of 14%).

SL velocities scale directly with sound speed; that is, a 1% error in sound speed results in a 1% error in velocity measurements. The following formula is used for post-processing corrections and can be directly applied to the output velocity data of the SL.

$$V_{true} = V_{orig} (C_{true} / C_{orig})$$

where:

V_{true} = Corrected velocity measurements
V_{orig} = Uncorrected (original) velocity measurements
C_{true} = True speed of sound
C_{orig} = Speed of sound used in original calculations

Errors in sound speed also affect the physical location of the SL measurement volume, although these errors are generally very small. To calculate the correct location of the SL measurement volume, use the following formula.

$$Z_{true} = Z_{orig} (C_{true} / C_{orig})$$

where:

Z_{true} = Corrected measurement volume location
Z_{orig} = Uncorrected (original) measurement volume location
C_{true} = True speed of sound
C_{orig} = Speed of sound used in original calculations