TRACEABILITY AND UNCERTAINTY IN FLOWRATE DETERMINATIONS
FOR THE ACCUSONIC MODEL 7510 MULTIPLE-PATH ULTRASONIC TRANSIT-TIME FLOWMETER

Introduction

The Accusonic Multi-path Ultrasonic Flowmeter operates on the principles set out in ISO 6416.
It uses the “Mean Section” flow integration method, in which the channel flow is computed from the sum of various panels. When only one path is operating, either because the water level is too low, or because other paths have failed, the mean velocity is computed from that path velocity using the relationship in ISO 6416 clause 2.10.3 and Table 4.
The uncertainty in the determination of flow is governed by uncertainties in:

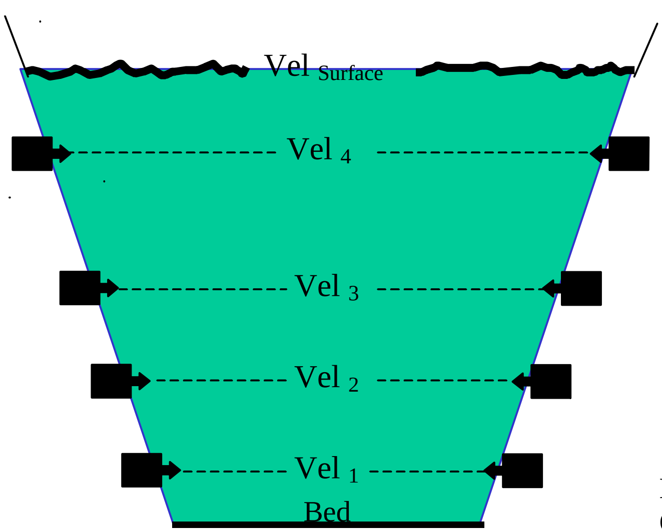
1. **Measurements of the channel dimensions and the stability of the channel structure**
   The dominant uncertainty is usually the elevation of the channel bed, where the effective position may be affected by silt deposits and debris, (stones, domestic refuse etc.).

2. **Measurement of water level**
   Water level measurements using an ultrasonic down-looking sensor may be affected by surface standing waves and foam, or by venturi effects around a submerged pressure transducer.

3. **Determination of the water velocity for each submerged path**
   Providing the channel and path geometry is correctly measured, the dominant uncertainty is due to skew flow. For all natural rivers and wide channels where there are upstream bends less than 10 channel widths upstream, the use of crossed paths is usually necessary to reduce this effect to less than 2%.
   This effect is discussed in ISO 6416 clauses 2.1.5 and Annex A. Errors as high as 30% have been encountered where this problem has not been correctly addressed.

4. **Uncertainties in signal timing**
   The 7510 flowmeter will determine signal time difference with an uncertainty of about 5 nano seconds. The uncertainty in velocity computation will be approximately:
   $5 \times 10^{-9} \times 1450^2 / (\text{Path length} \times 2 \cos \theta)$, where θ is the path angle.

5. **Assumptions made in the integration of the water velocities**
   The dominant uncertainties arise from extrapolation of the measured top & bottom acoustic path velocities to the surface and bottom, respectively. These extrapolations occur in the top and bottom "panels" of the flow cross section.



Top Panel
$Q_{Top} = ½ \text{ Top area} \times (Vel_{Surface} + Vel_4)$

Intermediate Panel
$Q_{Int} = ½ \text{ Area} \times (Vel_3 + Vel_4)$

Intermediate Panel
$Q_{Int} = ½ \text{ Area} \times (Vel_2 + Vel_3)$

Intermediate Panel
$Q_{Int} = ½ \text{ Area} \times (Vel_1 + Vel_2)$

Bottom Panel
$Q_{Bottom} = ½ \text{ Area} \times (1 + \text{Bed Coeff}) \times Vel_1$

Expected Uncertainty for a Typical Flowmeter Configuration.

When the water level is low, and only the lowest path can be used, the uncertainty is expected to be up to 15% for a natural channel and much less for a concrete-lined channel. The uncertainty can be reduced to 7% if it is possible to calibrate the system by carrying out a check gauging as described in ISO 748, or by using the methods described in ISO 6416. Alternatively, the velocity profile can be estimated when more than one path is operational, and this information used to assess the relation between the mean velocity and the readings from the one path.

Providing the topmost operating path is at an elevation not less than 0.7 of the depth, the uncertainty of the flowmeter when paths at 2 elevations are operational is about 5% to 7%, based on ISO 748 (1997) Table E4. When 3 paths are operational, the uncertainty falls to about 2 or 3%.
These uncertainties are estimated according to the methods described in the following standards, which are concerned with liquid flow in open channels:

BS / ISO 748: 1997: *Velocity Area Methods*
ISOTR 5168: 1998: *Evaluation of Uncertainties*
BS 3680 part 3E, ISO 6416 (1992): *Measurement of discharge by the ultrasonic (acoustic) method*
ISO / TAG 4: *Guide to the expression of uncertainty in measurement.*

An Example of an Uncertainty Calculation

For a rectangular concrete lined channel, 2-m wide and up to 3-m deep.
Minimum depth for flow measurement: 0.4 m
Minimum depth for accurate flow measurement: 0.75 m (expected uncertainty 7%)
Expected uncertainty at flows where depth exceeds 1.2 m to be 2%
The Flowmeter section is 20 m downstream of a bend or change in geometry.
Silt layer on the bed variable, up to 50mm on average.
Size of stones up to 100mm
Water velocity from 0.10 m/s to 3 m/s

Path elevations are chosen so that:

- The highest working (submerged) path is at least at an elevation of 0.6 x water depth.
- The lowest path will be as low as possible, but will not be obscured by debris on the bed.
- At the minimum depth for accurate flow measurement, 2 paths will be submerged.
- At a depth of 1.2 m, 3 paths will be operating.
- The top path will be at an elevation of 0.6 x maximum depth.
- Minimum submersion for a path to operate: 0.07 m (as advised in ISO 6416 clause 2.2.6)
- Path angle 45°, transducer frequency 500 kHz.

The path elevations will be: 0.3 m, 0.65 m, 1.1 m, 1.8m.

The dominant contributions to uncertainty are:

1. Water level measurement, where any errors are generally proportional to the percentage error in depth. Because the water velocity near the bed is lower than the average, especially when the depth is small, a 1-% error in depth will result in perhaps a 1.3-% error in flow.

2. Siltation: the uncertainty in the thickness of any silt layer on the bottom of the channel will have a proportional effect on the cross-section area. For small depths of flow, the errors will be greater.

3. Skew flow: in a channel of this type, there will be a very small rotational component to the water flow, caused by the bends upstream. This rotational component is likely to give a skew flow of about 1° at a given path elevation. If a path angle of 45° is used, this will cause an error of 1.7% in the velocity determination for that path. The rotational component of flow will be in one direction at the bottom of the channel, and the opposite direction at the top.

   If multiple paths are used, the effects will partially cancel, and the net uncertainty will be much less than 1,7% of flow.

4. Errors in surveying path lengths, path angles and channel width should be small and result in a contribution to uncertainty of less than 0.5% of flow. (The channel width may vary with time due to deposits of algae or grease on the walls. This component may require to be evaluated separately if it is significant).

5. Accuracy of signal timing: the Model 7510 flowmeter will determine the signal timing with an uncertainty of 5 nano seconds, which is equivalent in the proposed configuration to a velocity uncertainty of 2.5 mm/s. Under conditions when the water velocity is low, this effect will be greatest. At the minimum velocity of 0.1 m/s, it will cause an uncertainty of 2.5%, whereas at the maximum velocity it will be negligible, 0.1%.

6. The dominant uncertainty due to integration of the various panel contributions is in the bottom and top panels. The assumed relationship between the velocity for path 1 and the average velocity in the bottom panel is called the "Bottom Friction Coefficient" and for this type of channel is assumed to be 0.8, with an uncertainty of 5%. The bottom panel only represents a portion of the total cross section. Therefore, the contribution of this uncertainty to the total flow will be reduced roughly in proportion to the areas of the bottom panel and the total area of all panels.

   The average velocity in the top panel is computed by extrapolation of the velocities for paths 3 & 4 up to the water surface. From studies of the different behavior of flow in channels, this computation can be assumed to have an uncertainty of 3%. Again, the contribution of this uncertainty to the total flow will be reduced roughly in proportion to the areas of the top panel and the total area of all panels.

Integration uncertainty will be different at different depths and number of working paths. Some examples are:

a) Depth 0.5 m, flowrate 0.3 m^3/s, (mean velocity 0.3 m/s). One path operating.

   Component uncertainties:

Water level measurement ±10mm:	Flow uncertainty 2.6 %
Silt on bed 0 mm to 50 mm:	Flow uncertainty 5.0 %
Skew flow 1° caused by siltation:	Flow uncertainty 1.7 %
Survey errors:	Flow uncertainty 0.5 %
Signal timing:	Flow uncertainty 0.8 %
Integration, 2σ from ISO 6416 Table 4:	Flow uncertainty 4.0 %

   Total uncertainty in flow is the square root of the sum of the squares of the individual uncertainty components (see ISO 5168, or ISO *Guide to the Expression of Uncertainty*):
   i.e., $\sqrt{(2.6^2 + 5^2 + 1.7^2 + 0.5^2 + 0.8^2 + 4^2)} = 7.2\ \%$

b) Depth 2.5 m, flowrate 5 m^3/s, (mean velocity 1.0 m/s). Four paths operating.

Component uncertainties:

Water level measurement ±10mm:	Flow uncertainty 0.4%
Silt on bed 0 mm to 50 mm:	Flow uncertainty 1.0%
Skew flow 0.5°, multi-path cancellation:	Flow uncertainty 0.8%
Survey errors:	Flow uncertainty 0.5%
Signal timing:	Flow uncertainty 0.25%
Integration, 5% of bottom panel flow:	Flow uncertainty 0.6%
Integration, 3% of top panel flow:	Flow uncertainty 0.8%

Total uncertainty in flow is the square root of the sum of the squares of the individual uncertainty components: $\sqrt{(0.4^2 + 1.0^2 + 0.8^2 + 0.5^2 + 0.25^2 + 0.6^2 + 0.8^2)} = 1.8\%$

Accusonic Flowmeters

Since the early 1970's, Accusonic has supplied over 2,000 multi-path flowmeter systems worldwide for high-accuracy flow measurement in large pipes, open channels, and compound conduits. The potential accuracy of the flowmeters has been demonstrated by various independent trials, the latest for open channels being ENEL CRIS (Italy) in their report: "*Calibration of Multi-path Flowmeters installed in the Piave - S.Croce and Medium Piave Channels"* Rep. 1166-IUGI Feb. 1995.

For closed pipes running full, the flowmeters have been proven to be in compliance with the ASME Performance Test Code PTC 18-1992, where uncertainties of 0.5% to 1% for flowrate are required. Formal tests have been carried out by DWR, EPRI, Alden Research, New York Power Authority, Hydro-Quebec, ABB (UK), and Federal Technical Institute Zurich.

The Model 7510 Flowmeter utilizes the internationally accepted multiple-path ultrasonic (acoustic) transit-time method to determine the flow in open channels in compliance with the International Standard ISO 6416. The transit-time method is an absolute flow measurement method that does not require calibration by comparison to any other flow measurement method.

Water level measurements, together with accurately measured as-built dimensions of the installation, are required to calculate the flow area, and to determine the ratio of the path elevations to that of the water surface. From these, the average water velocity in the channel is estimated, based on an assumed vertically velocity profile (ISO 6416 clause 2.8.6 & Table 4) when only one path is operational, or on the "mean-section" method, (ISO 6416 clause 2.8.4.4) when paths at more than one elevation are operational. In addition, the Accusonic flowmeter computes the water velocity at the surface by a weighted extrapolation of the velocities from the two paths below the surface, and uses this to more accurately model the vertical velocity profile.

The Accusonic Model 7510 Flowmeter has the following features:

- The use of advanced Digital Signal Processing (DSP) technology for determining the precise time of travel of the acoustic signals, and the rejection of false signals.

- Automatic gain control to cater for deterioration in the signals which may occur due to suspended solids (signal energy margin typically a factor of 1000 or 30dB)

- Maximum distance between transducers and flowmeter console is 500m.
- Integral data logging of all variables on “Flash Memory” giving full diagnostic data.
- Measurements are independent of water temperature or salinity.
- Minimal sensor intrusion into flow with no significant flow obstruction.
- No moving parts or corrodible components giving long-term trouble-free performance.
- Self-diagnostic and measurement quality checking with automatic warning of degraded measurement conditions or questionable data.

Traceability of Flowrate Determination to the Standard

To have confidence in the ability of a flowmeter to give accurate data, it is first necessary to show that the performance of each part of the system can be traced to an accepted standard.
During the development of the flowmeter the following tests are specially conducted to demonstrate:

1. The Model 7510 Flowmeter is able to determine the timings of the acoustic signals with an uncertainty of 5 nano-seconds. The water velocity is correctly computed from the difference in the upstream and downstream path timings (together with the parameters of path length & angle).

   These tests were carried out on ten different closed pipe installations in Italy at zero flow and at known flows (±2%), using a digital storage oscilloscope as an independent timer. Exhaustive factory testing using a signal simulator has also demonstrated the functionality of the system.

2. The computation of wetted cross section area with respect to water level is correct, both for trapezoidal and circular pipes (±1%). This was checked in the software.

3. The computation of flow from the water velocities for different numbers of paths, the pipe geometry, and water levels is correct. This was done for a large number of conditions using a signal simulator to produce the water velocities.

4. The analog inputs from the various water level transmitters are correctly converted to the level readings in the flowmeter. These are checked at the factory using a variable current source and digital milli-ammeter.

5. The analog outputs for flow and level are correctly generated.

6. The internal data logger correctly records the current flowmeter variables at the time of each log

From the above tests, it has been shown that the Model 7510 Flowmeter performs as described in the manual, and that the hardware and software can be relied upon to behave in a known manner. It was also confirmed that the mathematical routines computed flow from the variables of level and velocity together with the parameters describing pipe geometry, in accordance with ISO 6416.

The next step in tracing the performance involves checking that the configuration of the flowmeter at each site is appropriate for the installation, that the parameters entered in the flowmeter are reasonable, and that they represent the as-built dimensions recorded during installation.

The parameters are:

Path Lengths
Path Angles
Path Elevations
Channel Dimensions
Transducer Characteristics
Water Level Sensor Characteristics

Various parameters are used to set the reasonableness test ranges for the measured variables.

The final phase involve live tests and observations on site to demonstrate that the operation of the flowmeter is compatible with the parameters which have been entered, and that the quality of the acoustic signals is such that reliable timing measurements can be assured.
These tests are listed in ISO 6416, clause 3.5.2.

Annex I

Typical Display of Flowmeter Variables

Flow: 0.671 **Volume:** 6.142 **Section Status:** Good
Average Level: 1.514 **Temp:** 15.200 **Integration:** MultiPath
Section Full: No **Learning:** No **Path Substitution:** No

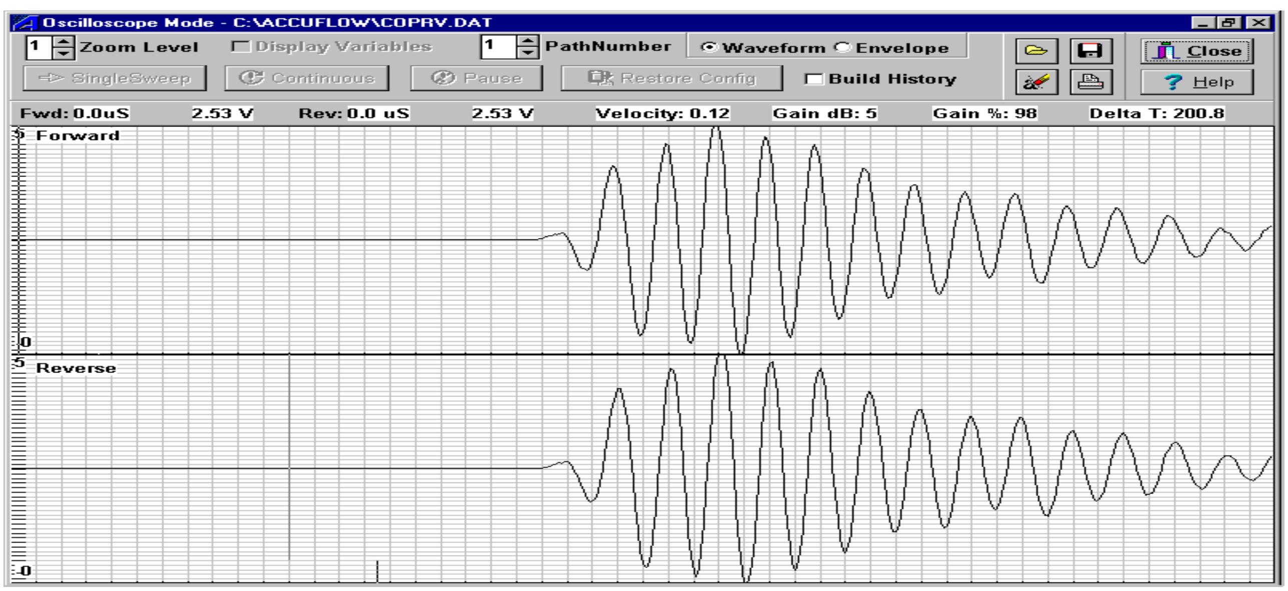
	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6	Path 7	Path 8	Path 9	Path 10
Velocity	0.085	0.077	0.093	0.09	0.094	0.096				
Gain dB	4.2	2.2	1.9	3.3	5.2	3.3				
Gain %	98.9	102	101.7	100.2	100.9	99.6				
S/N	27.8	28.3	27.8	27.9	27.9	27.8				
Travel Time uS										
Forward	4827.6	4819.1	4828.1	4823.6	4829.2	4828.4				
Reverse	4827.9	4819.4	4828.5	4824	4829.6	4828.9				
Delta Time nS	396.88	362.5	436.82	423.72	441.19	452.47				
VSound	1466.5	1468.1	1466.4	1466.7	1466	1466.3				
Envelope Time uS										
Forward	4827.6	4820	4828.1	4824.5	4830.2	4829.3				
Reverse	4827.9	4820.3	4828.5	4824.9	4830.6	4829.8				
Path Out of Water							X	X		
Path Fail							X	X		
Path Velocity Error										
Detection Method	Env	1st Neg	Env	1st Neg	1st Neg	1st Neg	Env	Env		
	Level 1	Level 2	Level 3	Level 4						
Level	1.514									
Status	Good									

Close Pause Resume Print Save ?

Section 1 Section 2 Section 3 Section 4 View

Ultrasonic Signal Waveforms

(*via Accuflow*® PC-Interface Software - Oscilloscope Mode)



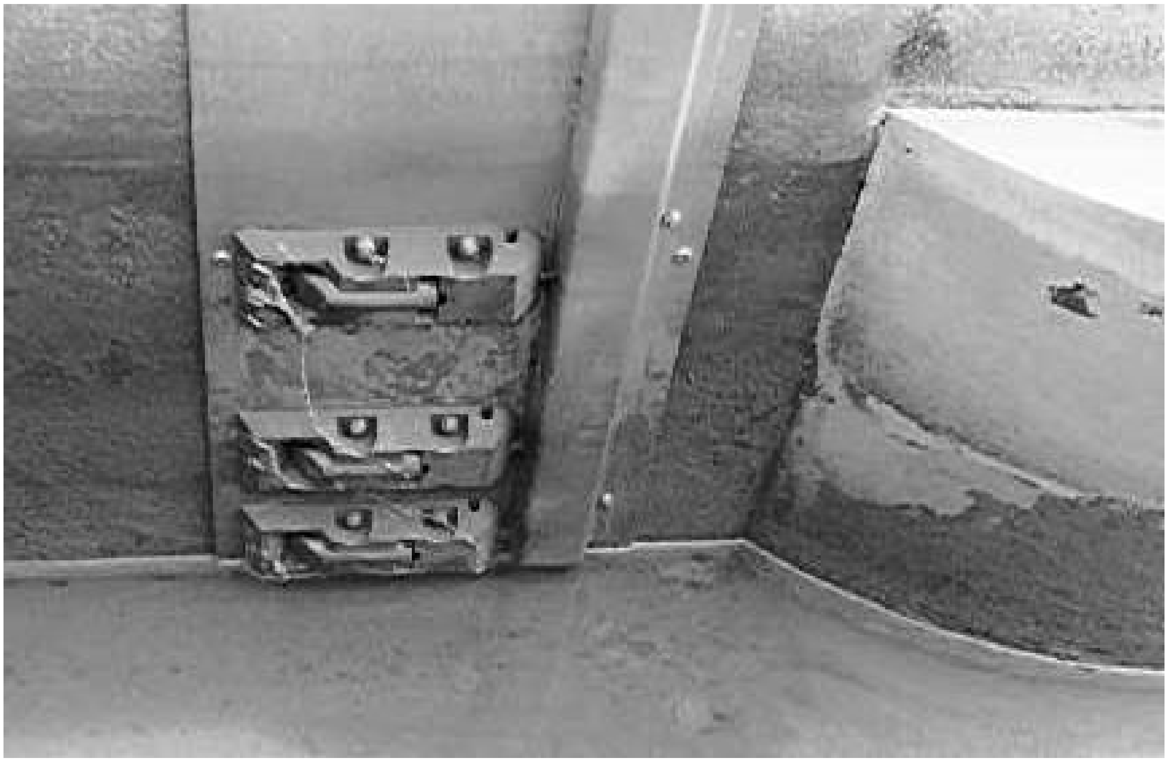


Figure 1
Model 7658 Transducers Mounted in a Sewage Channel

Annex II

FLOWMETER SYSTEM DESCRIPTION

A. Accusonic Model 7510 Flowmeter Console
The Accusonic Model 7510 Flowmeter is a Digital Signal Processor (DSP) based multi-path acoustic transit-time system. It measures discrete travel times to arrive at an average water velocity for each acoustic path.

Each acoustic signal is digitized at a rate of 10 million readings per second. From this the software is able to search the received waveform for a signal having the appropriate shape of envelope, determine its amplitude for adjusting the receiver gain, and then to compute the exact time of arrival of the first zero crossing.

If the signals are distorted by the presence of weed, air bubbles, or high sediment loads, the system automatically changes its signal detection mode to an "Envelope" method. Although the signal timing uncertainty is increased, reliable flow measurements can continue to be made under conditions which simpler technologies can not tolerate. By this means, true signals can be distinguished from spurious ones, thus reducing the incidence of both false and lost readings.

The Model 7510 Flowmeter incorporates an Automatic Gain Control (AGC) feature, which automatically adjusts the gain of the receiver according to the signal strength of the received pulse.

DSP technology improves the meter operation in high-noise environments. It allows the meter to ignore noise spikes and extraneous electrical signals, while still recovering the desired receive signal and its travel time. Multiple transmissions may be used, enabling the received signals to be “accumulated” to further increase the system signal-to-noise ratio.

The combined effect of these features ensures that only good signals are accepted and used for flow calculations.

For accurate flow measurement it is necessary to measure precisely the following parameters:

- Length of the acoustic path between each transducer pair
- Angle of the path with respect to the pipe/channel center line
- Cross-sectional flow area as a function of water level
- Elevations of the acoustic paths

The Model 7510 flowmeter console contains the following outputs and interfaces:

- Optionally up to four 4-20 mA analogue outputs, for output of flow, depth, or temperature.

- RS232 port for hand-held terminal or PC, for parameter entry and display of variables.

- RS-232 port for serial data communication and remote monitoring using a PC and modem (with either DOS or Windows operating systems).

- Optional internal data logger (requires a PC running under *Accuflow*® Windows®-based PC-interface software to upload the recorded data sets.

The flowmeter enclosure is rated NEMA 4X (IP65), with the hand-held module mounted inside.

The flowmeter contains diagnostic routines that test total system operation and performance.

When configured for remote access using a modem and telephone line, troubleshooting can be performed from a remote site or from the factory. Routine system maintenance is limited to periodic review of diagnostic results.

Using the remote access software, it is possible to inspect the values of all parameters and variables and to record them, inspect diagnostic data regarding acoustic signal strength and signal to noise characteristics, as well as display the actual acoustic signal waveforms in the "oscilloscope” mode.

The flowmeter is designed to return to full operation following power interruption, with all stored values retained.

B. Transducers

Model 7658 500-kHz ultrasonic transducers are recommended. These are supplied with streamlined PVC housings designed to prevent flow debris from hanging up and collecting on the transducers. The entire transducer assembly is constructed from non-corrodible materials, assuring superior long-term in situ performance. The transducer assemblies are installed by use of stainless steel mounting bolts to anchor the assemblies to the channel wall.

Water depth is determined using a down-looking ultrasonic sensor as well as a pressure transmitter as backup, both of which provide a 4-20mA analog signal.