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Evaluation of Xylem EXO Water-Quality Sondes and Sensors

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U.S. Department of the Interior
U.S. Geological Survey

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By Teri T. Snazelle

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Conversion Factors and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
feet (ft.)	3.28	meter (m)
	Volume	
cubic inch (in^3)	16.39	cubic centimeter (cm^3)
cubic inch (in^3)	0.01639	liter (L)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

1 torr is equal to 0.99999 millimeters of mercury.

Abbreviations

AMCO–AEPA	EPA-approved primary turbidity standards for calibrating turbidimeters and nephelometers
ASTM	American Society for Testing and Materials
C/T	conductivity/temperature
DCP	data collection platform
DO	dissolved oxygen
Ds	Hydrolab DataSonde
EPA	U.S. Environmental Protection Agency
ESPEC	manufacturer of environmental test chambers

EXO1	model of multiparameter sondes (manufactured by Xylem)
EXO2	model of multiparameter sondes (manufactured by Xylem)
FNU	formazin nephelometric units
HIF	Hydrologic Instrumentation Facility (USGS)
KOR	EXO products' communication software
LED	light emitting diode
mmHg	millimeters of mercury
NIST	National Institute of Standards and Technology
ORP	oxygen reduction potential
SC	specific conductance
SDI	serial data interface
SE	standard error
sn	serial number
SOA	signal output adapter
USGS	U.S. Geological Survey

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By Teri T. Snazelle

Abstract

Two models of multiparameter sondes manufactured by Xylem, parent company of Yellow Springs Incorporated (YSI)—EXO1 and EXO2—equipped with EXO conductivity/temperature (C/T), pH, dissolved oxygen (DO), and turbidity sensors, were evaluated by the U.S. Geological Survey (USGS) Hydrologic Instrumentation Facility. The sondes and sensors were evaluated in two phases for compliance with the manufacturer's specifications and the USGS acceptance criteria for continuous water-quality monitors. Phase one tested the accuracy of the water-quality sondes equipped: (a) with a C/T, pH, DO, and turbidity sensor by comparing the EXO sensors' measured values to those of an equivalently configured YSI 6920 V2-2 sensor, and (b) with multiple sensors of the same parameter type (such as three pH sensors and a C/T sensor) on a single sonde at room temperature and at an extended temperature range. In addition to accuracy, the communication protocols and the manufacturing specifications for range of detection and operating temperature were also tested during this phase. Phase two evaluated the sondes' performance in a surface-water environment by deploying an EXO1 and an EXO2 equipped with pH, C/T, DO, and turbidity sensors at USGS site 02492620 located at East Pearl River near Bay Saint Louis, Mississippi. The EXO sondes' temperature deviations from a certified YSI 4600 digital thermometer were within the ±0.2 degree Celsius (°C) USGS criteria, but were greater than the ±0.01 °C manufacturing specification. The conductivity sensors met the ±3 percent USGS criteria for specific conductance greater than 100 microsiemens per centimeter. The sensors met the more stringent ±0.5 percent manufacturing specification only at room temperature in the 250 microsiemens per centimeter (µS/cm) standard. The manufacturing and USGS criteria (±0.2 pH unit) were met in pH standards 4, 9.2, 10, and 12.45, but were not met in pH 1.68 standard. The DO sensors met both the ±0.3 milligram per liter (mg/L) USGS criteria and the ±1 percent manufacturing specification. The ±5 percent USGS criteria for turbidity in waters not exceeding 2,000 formazin nephelometric units (FNU) were met by the five turbidity sensors tested; however, all five sensors failed to meet these requirements at turbidities exceeding 2,000 FNU. The more stringent ±2 percent manufacturing turbidity specification for water with less than 1,000 FNU was met by only one of the five sensors tested. The results from the field deployment indicated acceptable agreement in temperature, specific conductance, pH, and DO between the EXO sondes, the site sonde, and the reference sonde. The EXO1 and EXO2 turbidity measurements differed from the site sonde by approximately 23 and 25 percent, respectively.

Introduction

The U.S. Geological Survey (USGS) Hydrologic Instrumentation Facility (HIF) evaluates the performance of instruments and equipment that are used to directly measure hydrologic data. Instrumentation and equipment evaluations are done primarily to determine if a particular device would be suitable for use by USGS personnel for hydrologic data collection. Test reports document the results at the time of the evaluation, and may or may not represent conditions resulting from updates and improvements to the instrumentation. The findings in this report are based upon the EXO communication software, KOR, release 1.0.1, and sonde firmware version 1.0.0. Sensor firmware versions were the following: conductivity/temperature, 1.0.3; pH, 1.0.14; dissolved oxygen (DO), 1.0.5; and turbidity, 1.0.1.

This report documents the laboratory and field evaluation of two Xylem-manufactured water-quality multiparameter sonde models, the EXO1 and EXO2, equipped with EXO conductivity/temperature (C/T), pH, DO, and turbidity sensors. The sondes and sensors were tested at the USGS HIF for compliance with the manufacturer's specifications and with USGS accuracy criteria as described in USGS Techniques and Methods 1–D3 "Guidelines and Standard Procedures for Continuous Water-Quality Monitors: Station Operation, Record Computation, and Data Reporting," (Wagner and others, 2006). In addition to accuracy, serial data interface (SDI–12) compliance and the effectiveness of Bluetooth communication were evaluated. An EXO2 sonde was compared to an equivalently configured Yellow Springs Incorporated (YSI) 6920 V2-2 (YSI 6920, water-quality sonde) to demonstrate that the EXOs performance was comparable to the YSI 6920 in field applications. The EXO sondes also were equipped with duplicate sensors (such as three pH sensors along with a C/T sensor on a single sonde) and tested for accuracy to not only evaluate the ability of the sensors to calibrate and function independently, but to make the test procedure more efficient and to conserve test standards. Accuracy was determined in the laboratory by comparing the sensor's measured values to certified National Institute of Standards and Technology (NIST)-traceable references when available. The accuracy of the EXO sondes and sensors in the field were evaluated by deploying them at USGS site 02492620 near Bay Saint Louis, Mississippi, and comparing their performance to well-maintained site and reference sondes. After a brief description of the two sonde models and the C/T, pH, DO, and turbidity water-quality sensors, the communication, laboratory, and field test procedures and results are described.

Description of Water-Quality Sondes and Sensors

EXO multiparameter sondes (fig. 1) are the latest generation of water-quality sondes marketed by YSI (YSI Inc., a Xylem brand, U.S.A.), and are designed as a replacement for the six series family of sondes. Overall, the EXO series sondes feature updated electrical connectors; strengthened housings for sonde and sensors; digital sensor technology with onboard signal processing and internal memory; and a centralized, antibiofouling wiper for improved long-term monitoring. The EXO1 (fig. 2, left) has four sensor ports, a peripheral port for power and communication, and an optional integral pressure transducer. The EXO2 (fig. 2, right) has seven sensor ports (the center port is generally used for the central wiper when it is installed on the sonde), and a six-pin expansion port for future interfacing with third party sensors (fig. 3). The expansion port comes with a protective screw cap and was inoperative at the time of this evaluation. The sondes have several communication protocols, including Bluetooth wireless, Universal Serial Bus (USB), RS–485, RS–232, and SDI–12. The sondes' SDI–12 communication protocol was tested with an NR Systems SDI–12 Verifier. EXOs can be operated with a computer, the EXO handheld, or a data logger; however, the EXO's data collection platform (DCP) signal output adapter (SOA) (fig. 4) is required to interface the sondes with a data logger that uses SDI–12 communication (Xylem, 2012a). EXO products (software, sensors, cables, handhelds, and so forth) are not interchangeable with YSI 6-series products. Table 1 lists the EXO sondes manufacturing specifications.

The EXO products' communication software is called KOR. Its basic menu structure is:

- Run - Displays live data from the sonde.
- Calibrate - Allows users to calibrate the sensors installed on the sonde.
- Deploy - Allows users to set up the logging features, including intervals and SDI–12 configurations.
- Data - Enables file transfers from the sonde or handheld.
- Options - Allows users to change application preferences, such as display units, sonde settings, and firmware updates.
- Connections - Allows users to connect to the sondes and devices, identifies the probes installed, and serves as the site for Bluetooth settings updates.

The "lite" version of KOR that is used by the EXO handheld does not require any software installation, and operates using Windows CE 5.0 (Xylem, 2012b). The KOR software for desktop and laptop computers is stored onto a USB flash drive and provided with every EXO sonde purchase. It is important to install the KOR software prior to any communication attempts to ensure the required drivers for sonde communication are installed along with KOR. After the KOR installation, the computer can communicate with the sonde through Bluetooth, or if Bluetooth is unavailable, through a USB dongle Bluetooth adapter. The following are the minimum computer requirements for the installation of the KOR software (Xylem, 2012b):

- Windows XP (service pack 3) or newer Windows operating platform (Windows 7 recommended).
- Microsoft .NET (any version from 2.0 through 3.5 Service Pack 1).
- 500 MB of hard disk space (1 GB recommended).
- 2 GB of RAM (4 GB recommended).
- Screen with resolution of 1280 x 800 dpi or greater.

Table 1. EXO1 and EXO2 manufacturing specifications (Xylem, 2012a).

[m, meter; ft., feet; MB, megabyte; USB, universal serial bus; SDI, serial data interface; VDC, volts of direct current; °C, degrees Celsius; kg, kilogram; lb, pound]

Specification	EXO1	EXO2
Operating depth	250 m, 820 ft. of water	250 m, 820 ft. of water.
Material	Resin, bronze, titanium, copper-nickel alloy, 316 stainless steel	Resin, bronze, titanium, copper-nickel alloy, 316 stainless steel.
Sensor ports	4	7 (6 when the central wiper used).
Peripheral ports	1 power and communication	1 power and communication. 1 auxiliary expansion port.
Internal Logging Memory Capacity	512 MB	512 MB
Operating System Software	Windows XP (service pack 3) or newer; Windows 7 recommended	Windows XP (service pack 3) or newer; Windows 7 recommended.
Communication Protocols	Bluetooth, USB, RS–485, RS–232, SDI–12	Bluetooth, USB, RS–485, RS–232, SDI–12.
Power Consumption	9–16 VDC	9–16 VDC
Operating Temperature	-5 to 50 °C	-5 to 50 °C
Dimensions	1.85 x 25.5 inches	3x28 inches
Weight	1.65 kg or 3.63 lb	2.65 kg or 5.83 lb

- Available USB 2.0 port.
- Internet access for software updates.
- The EXO sensors are “smart” sensors that maintain the sensor’s calibration information internally in the sensor’s software. Every EXO sensor has an internal reference thermistor used for quality-assurance purposes. Most sensors reference the conductivity/temperature sensor for temperature compensation; the exception is the turbidity sensor that references its own internal thermistor (Xylem, 2012a). The body of the sonde essentially serves as the data logger. Because the calibration is sensor specific, multiple sensors of the same parameter type can be calibrated on one sonde, with each calibration file collected one at a time. The EXO sensors have wet-mateable connections and will fit any sensor port. The sensors are automatically recognized by the sonde when they are installed, eliminating the need for manual port assignment.
- Three EXO1s and three EXO2s, along with serialized water-quality sensors, were evaluated using EXO handhelds, cables, and SOAs. Sensors included conductivity/temperature (C/T), pH, dissolved oxygen (DO), and turbidity. Table 2 summarizes the EXO manufacturer’s technical specifications for these sensors.

The C/T sensor uses a highly stable thermistor designed to reduce the potential for drift and internal nickel electrodes to measure conductivity. The temperature calibration is NIST traceable, and certified to be accurate within 0.01 °C. For conductivity, the voltage drop measured by the nickel electrodes is converted into a conductance value in millisiemens and is multiplied by a cell constant to convert to millisiemens per centimeter.

The EXO DO sensor is optically based, using luminescence-lifetime decay technology. Luminescence lifetime is defined as the time measured for a luminescence chemical to return from an excited to a relaxed state. The EXO optical DO measures luminescence lifetime using blue excitation light from a light emitting diode (LED) onto a dye-impregnated disk. The blue light causes the dye in the disk to luminesce and the luminescence lifetime is measured using a photodiode detector in the sensor. To

Table 2. Technical specifications for the tested sensors.

[µS/cm, microsiemens per centimeter; °C, degrees Celsius; %, percent; mg/L, milligram per liter; sat., saturation; FNU, formazin nephelometric units]

Sensor type	Temperature operating range (in °C)	Range of detection	Accuracy	Resolution
Conductance	–5–50	0.1–200,000 µS/cm	±0.5 % (0–100,000 µS/cm) ±1% (100,000–200,000 µS/cm)	0.1–10 µS/cm range dependent.
Temperature	n/a	5–50 °C	±0.01°C (-5 to 35 °C) ± 0.05°C (35 to 50 °C)	0.001 °C
Dissolved oxygen	–5–50	0.01–50 mg/L	±1% (0–20 mg/L) ±5% (20–50 mg/L)	0.1% air sat. 0.01 mg/L
pH	–5–50	0.01–14 units	±0.2 pH units	0.01 pH units
Turbidity	–5–50	0.01–4,000 FNU	±2% (0–999 FNU) ±5% (1,000–4,000 FNU)	0–999 FNU: 0.01 FNU 1,000–4,000 FNU: 0.1 FNU

increase accuracy and stability of the measurement, a reference emission is obtained using a red LED during the measurement cycle. The presence of oxygen quenches this process, and is inversely proportional to the lifetime luminescence; the higher the oxygen concentration, the shorter the lifetime luminescence (Mitchell, 2006).

The EXO pH sensor is a glass electrode type with two electrodes combined into the same probe tip; one as the measuring electrode and the other as the reference electrode. The EXO pH sensor comes in two varieties, as either a pH only or pH with oxygen reduction potential (pH/ORP). Each variety of EXO pH sensor features a removable sensor tip module and a reusable sensor body. In this report, we tested only the pH variety sensor. Internal-signal conditioning electronics improve the response and stability of the pH sensor, and electronic buffering in the pH sensor head reduces measurement noise.

The EXO turbidity sensor is a nonratiometric type, using an infrared (860±15 nanometer (nm)) excitation LED and an emitter-detector interference angle of 90 degrees. The sensor meets American Society for Testing and Materials (ASTM) standard D7315, the industry standard used to define turbidimeter design and measuring technique (American Society for Testing and Materials, 2012). The turbidity sensor contains an internal thermistor and reports output values raw or in formazin nephelometric units (FNU).

Test Procedures

Communication

Six sondes were evaluated with an NR Systems SDI–12 Verifier for compliance with the SDI–12 communication standard. The Verifier is a PC-based tool used to test the timing of SDI–12 bus transactions, and the ability of the sensors to respond correctly to SDI–12 commands. More information about the NR Systems SDI–12 Verifier can be found on the Web site at *http://www.SDI–12-verifier.com*. The effectiveness of the Bluetooth wireless communication between the EXOs and the PC, and between the sondes and the EXO handhelds, was also tested during the evaluation process.

Phase I—Laboratory Bench Testing

To evaluate the accuracy of the EXO sensors, several laboratory bench tests were conducted. DO concentration, specific conductance, temperature, turbidity, and pH measurements were collected and compared to test controls, which consisted of NIST-traceable standards, winkler titrations, and calculated theoretical DO values. Differences between the measured and control values were calculated and compared to the manufacturing specifications and USGS acceptance criteria (USGS criteria). Prior to testing, all EXO water-quality sensors were calibrated by following the protocol stated in the EXO User Manual, Revision C (Xylem, 2012b). When calibrated, the sensors passed the KOR software's quality control or "smart QC" requirements designed to flag errors in the calibration process.

The EXO C/T temperature readings were verified against a certified YSI 4600 digital thermometer calibrated to a ±0.015 °C tolerance. Secondary temperature readings on the pH and DO sensors used for quality-control purposes were not verified.

The C/T sensors were calibrated for specific conductance (SC) at 22 °C with a Ricca Chemical-certified standard of 1,000±0.4 percent. DO sensors were calibrated with a single DO concentration (100 percent), in air-saturated water at 21 °C. The pH sensors were calibrated at 23 °C with two standards, pH 7 and pH 10. Standards used for the pH calibration were certified to be within 0.01 pH unit of the standard value. The turbidity sensors were initially calibrated at room temperature using a two-point calibration with deionized water and an AMCO–AEPA-certified standard of 124±1 percent. The turbidity sensors were subsequently recalibrated at room temperature to improve the sensor accuracy in turbid waters greater than 2,000 FNU using the three-point calibration procedure with deionized water, 100, and 1,000 FNU StablCal turbidity standards. The StablCal turbidity standards used were certified accurate within ±0.018 percent of the standard value.

YSI recommends that optical-sensor calibration be verified without duplicated sensors of the same water-quality parameter on the sonde. Mike Lizotte, YSI Senior Application Specialist (oral commun., 4/24/13) has stated that verification of duplicate optical sensors on one sonde might prove problematic. Timing of the LEDs on the optical sensors are controlled during calibration to prevent interference with duplicate sensors. This is not the case when operating the sonde in real-time mode and interference can occur. The YSI recommendation was not adhered to for this evaluation.

Comparison Study

For the first test, an EXO1 sonde (serial number (sn) 207701) was fitted with a C/T, pH, DO, and turbidity sensor; its performance was compared to that of an equivalently configured YSI 6920 sensor. The YSI 6920 calibration was verified with a NIST-traceable Ricca chemical conductivity standard of 1,000±0.4 percent, a Fisherbrand pH 4 buffer with a certified error of ±0.01 pH unit, and a StablCal turbidity standard of 100 FNU±0.018 percent. The YSI 6920 DO sensor was calibrated at 100 percent DO using air-saturated water at approximately 25 °C at a barometric pressure of 760 millimeters of mercury (mmHg). Temperature measurements were compared to a certified YSI 4600 digital thermometer that was calibrated with NIST-traceable standards to a ±0.015 °C tolerance by the Lockheed Martin Metrology Center at Stennis Space Center, Mississippi.

The sondes, programmed to internally log every 15 minutes, were placed in a water bath in a solution of known pH, SC, and turbidity values. The two sondes and sensors were evaluated in the water-bath solution at room temperature and in an ESPEC environmental test chamber at four target water-bath temperatures—5, 15, 25, and 40 °C. The chamber was programmed to increase the water temperature to the first target temperature and then hold the temperature for a 2-hour soak. The process was repeated for the next target temperature until both sondes were tested at all four target temperatures. The USGS calibration criteria described in Wagner and others (2006) were applied to both sondes (table 3). The test acceptance criteria were derived by adding the water parameter-specific calibration criteria for the EXO and YSI 6920 sensors together, and is listed in table 3. The difference was calculated as the EXO measurement minus the YSI 6920 measurement; thus, a positive value indicated a high bias in the data, and a negative value indicated a low bias. The differences between the two sondes' readings were compared to the testing criteria to determine the accuracy of the EXO sensors. Differences larger than the summed accuracies of the two sensors indicate that the EXO sensor failed to meet the test acceptance criteria.

Accuracy Testing of EXO Sensors

To better assess the accuracy of EXO sensors, two EXO1s and two EXO2s sondes were configured with multiple sensors of the same water parameter (for example, 3 pH sensors). Each sonde configuration included at least one C/T sensor for temperature reference. The duplicate sensors were calibrated sequentially on the same sonde using the methods stated in the previous section. The configurations of the EXO1s and EXO2s are listed in table 4. In addition to evaluating their accuracy, this test also demonstrated the ability of the EXO sensors to maintain their calibrations "internally" per Xylem's design. The sondes were connected to a PC through a USB dongle and programmed through KOR to log internally to record the sensor's measured values. When available, the values from the duplicated sensors were compared to NIST-traceable standards for accuracy. The differences between the sensor measurements and the standard values for each test were compared to the USGS calibration criteria (Wagner and others, 2006) and to the manufacturing specifications.

Table 3. Test acceptance criteria of EXO1 (serial number 207700) to YSI 6920 V2-2 comparison.

[°C, degrees Celsius; µS/cm, microseimens per centimeter; %, percent; mg/L, milligrams per liter; FNU, formazin nephelometric units]

Water-quality parameter	Calibration criteria (Wagner and others, 2006)	Test acceptance criteria
Temperature (°C)	±0.2 °C	±0.4 °C
Specific conductance (µS/cm)	±5 µS/cm or ±3 percent of the measured value, whichever is greater	±6% of reading.
pH	±0.2 pH unit	±0.4 pH units
Dissolved oxygen (mg/L)	±0.3 mg/L	±0.6 mg/L
Turbidity (FNU)	±0.5 turbidity unit or ±5% of the measured value, whichever is greater	±10% of reading.

Table 4. Duplicated sensors test configuration.

[sn, serial number; DO, dissolved oxygen; C/T, conductance/temperature]

	Sonde 1	Sonde 2	Sonde 3	Sonde 4
Model	EXO1	EXO1	EXO2	EXO2
Sonde sn	207699	207700	208151	208152
Configuration	3 DO sensors/1 C/T sensor	3 C/T sensors/1 DO sensor	5 turbidity sensors/1 C/T sensor	5 pH sensors/1 C/T Sensor.

Dissolved Oxygen

Three DO sensors, installed with a C/T sensor on sonde 1 (EXO1 serial number (sn) 207699), were evaluated at four DO concentrations with theoretical values of 0 mg/L, 2.33 mg/L, 9.17 mg/L, and 13.18 mg/L. Sensor accuracy was determined by comparing the sensor's measured DO concentration to the theoretical value, and to the DO concentration obtained by Standard Methods 4500-O C, Winkler titration method (American Public Health Association, 1989). Four test results per sensor were collected at each concentration, and the average was compared to the theoretical and Winkler DO. An EXO handheld interfaced with the sonde was used to monitor the values, which were recorded in a laboratory book. The reference value for the theoretical DO concentration was calculated using Henry's Law:

$$p = k_H c$$

where:

p = the partial pressure of a gas above the solution in atmospheres;
c = the concentration of the gas in the solution in moles per Liter; and
k_H = Henry's constant in moles per atmosphere.

Henry's Law states that the amount of a gas that dissolves in a solution at a constant temperature is directly proportional to the partial pressure of the gas in equilibrium with the solution (Battino and Clever, 1966).

A calibrated YSI 6920 V2 was used as an additional control during the testing. The YSI 6920 sensor's accuracy was verified prior to testing by comparing its temperature readings to a certified YSI 4600 digital thermometer, and its barometric pressure measurements to a calibrated Mensor barometer (model DPG 2300, Mensor, Inc., San Marcos, Texas). The two lowest DO concentrations were created in a sealed water bath. The 0-mg/L DO concentration was prepared by pumping 100 percent nitrogen gas into the water bath at room temperature until the oxygen in the water was depleted. The sparging process took approximately 60 minutes to complete, and the water temperature and the barometric pressure were carefully monitored during the process to ensure that a stable environment was maintained. The 2.33-mg/L DO concentration was created by introducing a gas mixture of 95 percent nitrogen and 5 percent oxygen into the sealed water bath at room temperature. The gas mixture was bubbled into the water bath for 60 minutes until the DO concentration stabilized near 24 percent. The atmospheric pressure at the time of the 2.33-mg/L DO measurements was 760.2 mmHg at 19 °C. Atmospheric pressure was 763.8 mmHg at 21.5 °C when the measurements for the 0-mg/L test were collected.

To create the 9.17-mg/L DO concentration test conditions, a water bath at room temperature was aerated by an air stone connected to a small aquarium pump for approximately 45 minutes until the water was fully saturated. To create the theoretical DO concentration of 13.18 mg/L, the aerated water bath was chilled to 5 °C in an ESPEC environmental chamber. Water-bath temperature was monitored using the certified YSI 4600 digital thermometer.

Conductivity/Temperature-, Turbidity-, and pH-Sensors Tests

Room-temperature and the target-temperature tests of the C/T, turbidity, and pH sensors were conducted by filling triple-rinsed EXO calibration cups with the proper standard solution. The sondes measured the standard every 15 minutes, and the central wipers of the EXO2s were programmed to engage every 30 minutes. The environmental chamber was used to test the EXOs at the target temperatures (5, 15, 25, and 40 °C). Standard temperature was monitored with the certified YSI 4600 digital thermometer, and data collected outside ±0.2 °C of the target temperature (the soak period) were disregarded. With the temperature outliers removed, the datasets for C/T, pH, and turbidity averaged 5 to 10 data points per extended temperature. Data were averaged, and the standard error of the mean was calculated. Standard error of the mean estimates the standard deviation of the population of data points and is represented in the conductivity and pH data plots as vertical error bars.

Three C/T and one DO sensor were installed on sonde 2 (EXO1 sn 207700), and were evaluated at room temperature in five conductivity standards: 50; 250; 5,000; 10,000; and 50,000 µS/cm. The sonde was connected to a PC through the USB dongle, and set to internally log the measured values in KOR. The sensors were evaluated at the previously described target temperatures in two conductivity standards: 250 and 10,000 µS/cm. Conductivity standards used in the evaluation were accurate to a minimum of ±0.4 percent of the standard value.

Five turbidity sensors and one C/T sensor were installed on sonde 3 (sn 208151). To optimize the detection range, the turbidity sensors were recalibrated prior to the additional testing by following the three-point procedure described in the EXO User Manual with 0, 100, and 1,000 FNU StablCal turbidity standards (Xylem, 2012b).

Particle settling was an issue during the turbidity testing. Initially, a stir bar and plate were used to maintain the suspension of the standard, but after several trials, manual mixing of the suspension proved to work best, and was ultimately used for the recorded values. Sonde 3 was evaluated with only one turbidity standard over the extended temperature range due to settling of the standard particulates. The turbidity standard was manually resuspended immediately prior to sensor measurements.

NIST does not certify turbidity standards; however, formazin, AMCO–AEPA, and StablCal turbidity standards are accepted by the U.S. Environmental Protection Agency (EPA) as primary calibration standards for turbidimeters (U.S. Environmental Protection Agency, 1999). The uncertainty of the formazin turbidity standards was estimated at 3.5 percent by summing the 1-percent lot-to-lot variation, a small random error accrued through the making of standard dilutions, and the 2-percent certified error of the stock 4,000 FNU standard. The uncertainty for the StablCal turbidity standards was estimated at less than 2 percent at a 95-percent confidence, and was calculated by doubling the sum of the squares of the 4,000 FNU StablCal stock percent error and the mean percent deviation of five replicates of the stock dilution standards analyzed on a calibrated Hach 2100N turbidimeter. No serial dilutions were used in the evaluation.

Formazin is considered the primary standard for turbidimeter calibration in the United States, and because most turbidity measurement technologies are characterized by formazin, it is the best choice as a calibration standard (Sadar, Hach Application Notes). In addition, formazin or "stabilized" formazin provides a common reference for sensor comparisons to the past generation YSI turbidimeters. Turbidity sensor detection range in this report was determined by its performance in formazin and StablCal turbidity standard by Hach Company.

Five pH sensors, installed on sonde 4 (EXO1 sn 208152) with a C/T sensor, were evaluated at room temperature in pH standards of 1.68, 4.00, 9.18, and 12.45; and at 5, 15, 25, and 40 °C in pH standards 4 and 10. For each standard, the sensors were submerged and given 2 minutes for temperature stabilization before the measured values and temperature were recorded. Five measurements for each standard were averaged and compared to the reference standard value at each target temperature. The pH standards used in this evaluation were certified accurate within ±0.01 pH units at 25 °C. The temperature-adjusted pH value provided on the manufacturer's certificate of analysis was used as the standard value during the target temperature tests.

Phase II—Field Testing

For phase II of the evaluation, an EXO1 and an EXO2 fitted with calibrated C/T, pH, DO, and turbidity sensors were deployed at USGS site 02492620 from March 13 to May 7, 2013. Both EXO units met the USGS-recommended calibration criteria prior to deployment (Wagner and others, 2006). The sondes were programmed to measure every 15 minutes and to log internally. The wiper on the EXO2 was programmed to engage every 30 minutes. The EXO1 and EXO2 were deployed adjacent to a Hydrolab DataSonde (Ds) 5X (sn 200266), which was cleaned and calibration verified as part of the routine weekly site visits. Reference sonde (sn 12C101328), aYSI 6920 V2-2 sensor, was temporarily deployed during the site visits to monitor the accuracy of the site sonde and serve as a secondary reference for the EXOs. The EXO sondes received biweekly cleaning and calibration verification checks. A site log was kept documenting the date and time of each site visit, the site conditions, the calibration verification results, and any recalibration information. Sonde accuracy was determined by the difference between the EXO and the Hydrolab Ds5X site sonde's measurements; however, the measurement difference between the EXOs and the reference sonde was also recorded. Difference was calculated as EXO measurement minus the Ds5X (reference); therefore, positive values indicated a high bias in the data, and negative values indicated a low bias.

USGS site 02492620 is located on the East Pearl River in Hancock County, Mississippi. The site is located in a tidally affected reach of the river and frequently becomes brackish in the fall and winter. During the spring and summer months, the water is normally fresh (less than 100 µS/cm) and clear (less than 150 FNU). Low-conductance water can cause electrochemical sensors, such as pH, to respond more slowly, drift, and fail to reproduce calibration results. Chapter 6 of the Field Manual, Use of Multiparameter Instruments for Routine Field Measurements (Gibs and others, 2007), notes that "the field measurement procedures implemented depend on the type of water body for which the chemical and physical properties are being determined." Table 6.8-5 of chapter 6.8.3 recommends allowing sensor readings to stabilize within ±5 percent for SC less than or equal to 100 µS/cm, ±10 percent for turbidity less than 100 FNU, and ±0.3 pH units for stabilization of pH sensors in low-conductance waters (less than 75 µS/cm). To compensate for any measurement differences between the reference and EXO sondes caused when testing low-conductance water, and to also adjust for any inherent manufacturing differences in measurement, these recommendations were modified and adopted as the acceptance criteria for phase II (table 5). To meet the acceptance criteria, the differences between the EXO sensors and the site monitor's sensors should be less than the allowable deviation. Measurement differences greater than the allowable deviation indicated a failure to meet the criteria.

Table 5. Hydrologic Instrumentation Facility (HIF)-modified U.S. Geological Survey acceptance criteria for phase II comparison testing of the EXOs and the site and reference sondes.

[°C, degrees Celsius; %, percent; mg/L, milligrams per liter]

Water-quality parameter	Calibration criteria (Wagner and others, 2006)
Temperature	±0.4 °C
Specific conductance	±10% of reading
Dissolved oxygen	±0.6 mg/L
pH	±0.6 pH units
Turbidity	± 10% of reading

Test Results

Communication

The EXO's DCP SOA (fig. 4) used to convert serial communications from an EXO sonde to SDI–12 passed the NR Systems SDI–12 verification test. Interfacing the SOA to the EXO communication cable and the data logger proved difficult. The SOA is not waterproof and must be protected from the elements. Other communication tests involving the DCP SOA showed ambiguous results. If a sonde is equipped with multiple sensors of the same parameter type, the sonde will internally log the information from both sensors; however, the sonde will only transmit the value from the first of the duplicate sensors when communicating to a DCP through SDI–12. For example, a sonde with two pH sensors will report the first sensor's measurement for each duplicate sensor (in this case, twice).

The Bluetooth feature of the EXO products provides cable-free communication between the sonde and the EXO handheld or computer. The usefulness of the Bluetooth feature, however, is limited because radio waves do not penetrate water, and the Bluetooth communication link failed when the EXO sonde was submerged in water. The transfer of data files from the sonde to the handheld was also problematic. Several attempts were made with two different EXO handhelds before a successful data transfer was accomplished through Bluetooth. Data transfer was easily accomplished using the USB dongle adapter and cable, but the handheld usually required fresh batteries to successfully transfer a file of significant size using Bluetooth. It was not uncommon for a handheld with fresh batteries to power down after only one site visit.

Phase I—Laboratory Bench Testing

Water temperature was carefully monitored throughout the evaluation with a calibrated YSI 4600 digital thermometer to verify the sensors' ability to compensate for temperature. The C/T sensor water-bath temperature readings met the USGS criteria of ± 0.2 °C during the room-temperature tests and during the extended (5, 15, 25, and 40 °C) environmental chamber tests. The average difference in temperature between the EXO sensors and the certified digital thermometer was 0.08 °C. This average was calculated from data pooled from the sonde comparison and the sensor tests, and included all five sondes (three EXO1s and two EXO2s).

Comparison Study

Data collected during the comparison of the EXO1 and the YSI 6920 V2-2 showed good agreement between the two units at bath temperatures that ranged from 9.7 to 23.4 °C. The maximum differences between the units met the test acceptance criteria and were the following: temperature, –0.11 °C; specific conductance, 1.32 percent; pH, 0.21 pH unit; DO, 0.34 mg/L; and turbidity, –8.2 percent.

The results from the comparison test indicated that the EXO smart sensors perform similarly to the YSI 6-series sensors (table 6).

Table 6. Results of EXO1 (sn 207700) to YSI 6920 V2-2 comparison.

[Max, maximum; Min, minimum; Temp, temperature; °C, degrees Celsius; SC, specific conductance; µS/cm, microseimens per centimeter; %, percent; DO, dissolved oxygen; mg/L, milligrams per liter; FNU, formazin nephelometric units]

Water–quality parameter	EXO:6920 Max difference	EXO:6920 Mean difference	EXO Min reading	EXO Max reading	6920 Min reading	6920 Max reading
Temp (°C)	–0.11 °C	–0.04 °C	9.77 °C	23.41 °C	9.77 °C	23.42 °C
SC (µS/cm)	–1.32 %	–0.95 %	395.77 µS/cm	400.41 µS/cm	400 µS/cm	403 µS/cm
pH (pH units)	0.21 pH units	0.17 pH units	8.44 pH units	8.57 pH units	8.30 pH units	8.38 pH units
DO (mg/L)	0.34 mg/L	0.02 mg/L	7.53 mg/L	8.35 mg/L	7.65 mg/L	8.38 mg/L
Turbidity (FNU)	–8.2%	–7.6%	82.7 FNU	83.4 FNU	89.3 FNU	90.2 FNU

Accuracy Testing of EXO Sensors

Dissolved Oxygen Sensor Test Results

Three EXO DO sensors were tested for accuracy in four theoretical DO concentrations of 0, 2.33, 9.17, and 13.18 mg/L. The differences between the measured DO and the Winkler titration DO are shown in figure 5. Vertical error bars in figure 5 represent the expanded uncertainty at 95-percent confidence of the Winkler titrations and was calculated from the sum of the squares of 0.1 mg/L-average deviation in replicates, 0.06 mg/L (0.5 percent) error from the reagents used in the titrations, and 0.2 mg/L error from the glassware. Sensor measurements were precise with an average difference of 0.01 mg/L between the replicates. The maximum difference observed during the test occurred at 0 mg/L and was likely due to an incomplete sealing of the DO test chamber from the atmosphere. All three sensors met the ±0.3 mg/L USGS criteria, and also met the ±1 percent manufacturing specification when the titration uncertainty was considered.

In figure 6, the measured DO concentrations are compared to the theoretical concentrations computed using Henry's Law. Vertical error bars in figure 6 represent the expanded uncertainty at 95-percent confidence of the theoretical calculations, and was derived from the sum of the squares of the ±0.2 °C thermometer error and 0.0015 mg/L error from the Mensor barometer used in the calculation of Henry's Constant. The maximum difference of the three sensors in four DO concentrations was –0.27 mg/L, and the average difference was 0.10 mg/L. When compared to the theoretical value, the USGS criteria for DO was met; however, the ±1 percent manufacturing specification was not met.

Conductivity/Temperature Sensor Test Results

Three C/T sensors were evaluated at room temperature (25 °C) in the five conductivity standards of 50; 250; 5,000; 10,000; and 50,000 µS/cm (fig. 7). All three sensors met the USGS criteria of ±3 percent (Wagner and others, 2006) for specific conductance, but failed to meet the more stringent ±0.5 percent manufacturing specification. The results from the target temperature tests are shown in figure 8. In the first standard, 250±0.4 percent µS/cm, the sensors showed good agreement at 5, 15, and 25 °C, but were biased high at 40 °C. The average difference between the sensors and the 250 µS/cm standard at 40 °C was 9.2 µS/cm, which exceeded the 7.5 µS/cm USGS criteria upper limit. This pattern reversed in the 10,000±0.1 percent µS/cm standard. In this standard, the sensors met USGS criteria at 15, 25, and 40 °C, but were biased high at 5 °C. The mean difference between the sensors and the 10,000 µS/cm standard at 5 °C was 391.7 µS/cm, which also exceeded the upper limit (300 µS/cm). In both standards, the sensors demonstrated good precision. The average standard deviation was 0.34 µS/cm in the 250 µS/cm standard and 5.2 µS/cm in the 10,000 µS/cm standard.

Turbidity-Sensor Test Results

The evaluation of the EXO turbidity sensors proved problematic. The results from the room-temperature formazin testing of the turbidity sensors with a three-point calibration are shown in figure 9. The difference between the mean of five replicates and the standard turbidity value is plotted for each standard. All five sensors met the ±5 percent USGS criteria in turbidities to 2,000 FNU, and sensor sn 208994 met the criteria at 2,500 FNU when the uncertainty of the measurement was included.

Despite the close proximity of the sensors on the same sonde, significant variability in the readings was observed in all five sensors and occurred in every turbidity standard. The average standard deviation of the dataset—five replicates per sensor (five sensors) in seven standards—was 19.5 FNU. The variability in the readings may have been due to interference caused by the uncontrolled lighting in run mode between sensors, which YSI predicted might happen. However, significant variability in the readings occurred even when the duplicated sensors were removed from the sonde.

The ±5 percent USGS criteria was met during the extended temperature testing of the sensors in a 40 FNU StablCal turbidity standard. The ±2 percent manufacturing specification for turbidities less than 1,000 FNU was also met. Table 7 summarizes the results of the target temperature test. The mean was calculated from five replicates collected within ±0.2 °C of each target temperature.

YSI was notified about the detection-range suppression that was observed during the room-temperature tests and they recommended that the turbidity sensors be recalibrated using AMCO–AEPA (AMCO-clear) standards because “the accuracy specification for the EXO turbidity sensor was determined using AMCO–AEPA standards because they are more stable (no settling) and are easier and safer to dilute then Formazin. Any accuracy checks must be made using these standards because of the difficulties stated” (Mike Lizotte, YSI, oral commun., 4/23/13). Instead of recalibrating the turbidity sensors, four of the sensors with three-point StablCal calibrations were installed along with a C/T sensor onto one EXO2 sonde, and tested in the 4,000 FNU AMCO–AEPA turbidity standard provided by YSI. The results in table 8 show good agreement with the AMCO–AEPA turbidity standard. The difference from the standard ranged from 0.07 to 2.46 percent for the four tested sensors, and was computed as the measured reading minus the standard value. When the same sensors were again subjected to the 4,000 FNU StablCal standard, the differences increased significantly from 8.28 to 12.81 percent. The results of this test indicated the EXO turbidity sensors met the manufacturing and USGS criteria in AMCO–AEPA, but not in StablCal or formazin turbidity standards. YSI has subsequently redefined the specifications for the accuracy of sensors calibrated in AMCO–AEPA turbidity standards on their Web site as ±15 percent in turbid waters greater than 1,000 FNU. This correction can be found at http://www.exowater.com/sensors.

pH Sensor Test Results

Five pH sensors were subjected to four standards at room temperature and two standards at 5, 15, 25, and 40 °C. The results of the room-temperature testing are shown in figure 10. Vertical error bars represent the maximum standard error (SE) of the mean. The maximum SE recorded during the evaluation was produced by sensor sn 208070, and was 0.10 pH unit. For pH, the manufacturing specification matched the USGS criteria at ±0.2 pH unit. All five sensors met the USGS criteria at pH 4.0, 9.2, and 12.5. Four of the five sensors failed to meet the specifications at pH 1.68. Sensor sn 208105 narrowly met the requirements with a mean difference of 0.21 pH unit and a SE of ±0.02 pH unit.

As shown in figure 11, the sensors met USGS criteria in the pH 4 standard for all four target temperatures. In the pH 10 standard, three of the five sensors—sn 208069, sn 208105, and sn 208106—were slightly out of compliance with USGS criteria at 25 °C (fig. 5; right), with a mean difference of 0.22, 0.25, and 0.24 pH unit, respectively. At 40 °C, the mean difference was 0.20 pH unit for all five sensors. The replicates in pH 10 were very precise at each temperature, and the largest calculated SE for the sensors across the temperature range was 0.01 pH unit.

Table 7. Results from the extended temperature test for five EXO turbidity sensors in 40 FNU StablCal turbidity standard.

[°C, degrees Celsius; sn, serial number; FNU, formazin nephelometric units]

	Temperature (°C)	Sensor sn 208995	Sensor sn 208991	Sensor sn 208992	Sensor sn 208994	Sensor sn 208996	Group average
		All turbidity readings in FNU					
Mean	5	42.01	41.93	40.72	39.61	40.71	40.99
	15	39.22	39.81	40.74	40.30	40.32	40.08
	25	42.81	41.94	44.83	42.64	41.61	42.76
	40	40.71	41.44	40.41	42.33	40.21	41.02
Minimum	All	33.22	35.63	35.73	35.21	35.10	
Maximum	All	46.41	45.80	46.82	46.34	44.43	
Standard deviation	All	3.25	2.71	3.02	3.15	2.16	

Table 8. Mean readings from five replicates of the EXO turbidity sensors in 4,000 FNU StablCal and AMCO–AEPA turbidity standards.

[FNU, formazin nephelometric units]

EXO sensor serial number	StablCal		AMCO–AEPA	
	Average reading in FNU	Percent difference	Average reading in FNU	Percent difference
208995	3,668.49	8.28	4,002.83	0.07
208991	3,578.81	10.53	3,922.24	1.95
208992	3,487.63	12.81	3,949.91	1.27
208994	3,583.01	10.43	3,901.62	2.46

Phase II—Field Testing

A summary of the differences in temperature, pH, DO, specific conductance, and turbidity measurements between the EXO sondes and the Hydrolab DataSonde 5X site monitor is shown in table 9. None of the EXO's measurements were corrected for fouling or drift. The average difference between the EXO sondes and the site and reference sondes' temperature readings was well within the allowable testing criteria of ±0.4 °C (fig. 12). Average temperature differences from the Hydrolab DataSonde 5X site sonde of 0.04 °C and 0.05 °C were recorded for the EXO1 and EXO2, respectively. Table 10 shows the differences between the EXOs' and the reference sonde's measurements recorded during site visits. EXO temperature differed from the YSI 6920 V2-2 reference sonde by an average of 0.04 °C for the EXO1 and 0.03 °C for the EXO2.

Table 9. Summary of the phase II field testing measurements by the Hydrolab DataSonde 5X (Ds5X) site sonde and the EXO1 and EXO2 sondes.

[Min, minimum; Max, maximum; Temp, temperature; °C, degrees Celsius; DO, dissolved oxygen; mg/L, milligrams per liter; SC, specific conductance; µS/cm, microsiemens per centimeter; FNU, formazin nephelometric units]

	DS5X Mean	DS5X Min	DS5X Max	EXO1 Mean	EXO1 Min	EXO1 Max	EXO2 Mean	EXO2 Min	EXO2 Max
Temp (°C)	18.17	14.20	21.70	18.13	14.20	21.60	18.12	14.20	21.59
pH (pH units)	5.95	5.33	6.38	6.36	5.82	6.66	6.31	5.76	6.66
DO (mg/L)	7.51	5.50	9.00	7.65	5.57	9.20	7.78	5.67	9.32
SC (µS/cm)	49.01	28.00	81.00	51.41	29.45	83.61	51.62	29.77	84.06
Turbidity (FNU)	41.73	19.00	117.00	32.00	17.32	110.58	31.15	19.12	100.41

Table 10. Summary of the average differences in measurements between the YSI 6920 V2-2 reference sonde and the EXO sondes.

[Temp, temperature; °C, degrees Celsius; DO, dissolved oxygen; mg/L, milligrams per liter; SC, specific conductance; µS/cm, microsiemens per centimeter; FNU, formazin nephelometric units]

Average difference	EXO1	EXO2	Test-acceptance criteria
Temp (°C)	0.04	0.02	±0.4
pH (pH units)	–0.03	–0.09	±0.6
DO (mg/L)	–0.02	0.12	±0.6
SC (percent)	–2.97	–1.27	±10
Turbidity (percent)	–3.33	–0.47	±10

The mean percent difference between the EXO1 specific conductance and the Hydrolab DataSonde 5X was 4.9 percent. EXO2 data differed from the Hydrolab DataSonde 5X with a mean percent difference of 5.3 percent, which was well within the acceptance criteria of ±10 percent. In figure 13, the percent differences between SC measurements for the EXO sondes' and the site and reference sondes' are plotted along with the stage and discharge data recorded during the testing period. Most of the data points are well within the ±10 percent criteria, although several exceeded the upper acceptance limit. The EXO1 outliers observed on April 3, 2013, and at the end of the testing period, do not show a fouling trend. The EXO2 data from the first week of May 2013 indicated an upward trend, and could be the result of biofouling. The sondes were cleaned on March 20, 2013, and were not serviced again for 2 weeks. The last scheduled site visit was on April 24, 2013.

The phase II results from the dissolved oxygen testing are shown in figure 14. The average difference was 0.14 mg/L between the EXO1 DO and the Hydrolab DataSonde 5X, and 0.27 mg/L between the EXO2 and the Hydrolab DataSonde 5X. Both units easily met the testing criteria of ±0.6 mg/L. Data from the EXO2 showed evidence of trending towards the end of the evaluation period, indicating a potential fouling issue.

The results of the pH testing are shown in figure 15. Both units met the acceptance criteria of the test plan and the EXO2 data showed marginally better agreement with the Hydrolab DataSonde 5X. Comparing the EXO2's mean difference of 0.36 pH unit to the 0.41-pH unit mean difference of the EXO1 indicated only a slight improvement from the central wiper (0.05 pH unit). The EXO2-to-Hydrolab DataSonde 5X difference standard deviation was 0.07 pH unit. For the EXO1, the standard deviation was only 0.08 pH unit. The average pH difference between the EXOs and the YSI 6920 V2-2 was -0.03 pH unit for the EXO2 and -0.09 pH unit for the EXO1.

Results from the field-deployment turbidity test are shown in figure 16. When compared to the Hydrolab DataSonde 5X site sensor, the EXO sensors showed a low bias. On average, the EXO1 data were 23 percent lower than turbidity reported by the site sonde. The EXO2 turbidity data averaged 25 percent lower than data from the site sonde. The sensors tracked the recorded fluctuations in turbidity effectively. The low bias in the data could be attributed to differences in sensor design, even though all three models are nephelometric sensors. The EXO sondes' measured turbidity differed from the reference sonde's an average of –7.1 percent, and met the testing criteria of ±10 percent.

The central wiper on the EXO2 is designed to reduce fouling and to extend the interval between instrument servicing. The wiper seemed to have a limited effect on reducing fouling on the pH sensors, and little or no effect on reducing fouling on the DO and C/T sensors; however, it is important to remember that sondes were serviced every 2 weeks, so extensive fouling was limited. One possible explanation for the discrepancy is in the sensor port assignment. Because these sensors are universal, they can be installed into any available port on the sonde. To prepare for the evaluation, the sensors were installed on the EXO2 in the following order (fig. 17): port 1—turbidity; port 2—pH; port 3—DO; port 4—empty; port 5—empty; and port 6—C/T.

Early versions of the EXO2's central wiper (evaluated in this report) performed two rotations counterclockwise from port 1 to port 6. The central wiper then reversed and wiped once clockwise from port 6 back through port 1 before it parked in the wiper "garage." This wiping process may have redistributed the fouling from the first sensors in the rotation to those located later in the wiper rotation. Although unproven, this could explain why the DO and C/T sensors on the EXO2 performed slightly worse than those located on the EXO1 without a central wiper. Newer versions of the central wiper now perform a two-and-two rotation: two rotations counterclockwise, and then two rotations clockwise before parking.

Summary

The EXO sondes and sensors were evaluated in two phases: in phase I for compliance to USGS accuracy criteria and to validate the manufacturer's technical specifications, and in phase II for performance in a field application. In addition to accuracy, the EXO products were also evaluated for detection range, operating temperature, and communication. The field application compared the performance of the EXO1 and EXO2 sondes equipped with C/T, pH, DO, and turbidity sensors to a YSI 6920 V2-2 sensor and a Hydrolab DataSonde 5X sensor in the field.

The EXO's DCP SOA is required to interface the sonde with a DCP that uses SDI–12 or RS–232 communication. The SOA is susceptible to moisture, and must be protected from environmental effects. Most of the evaluation results were in compliance to the USGS criteria for accuracy. Some of the results did not meet manufacturing specifications and suggest that the manufacturing specifications for accuracy and detection range may be exaggerated. The USGS criteria for temperature, specific conductance, and DO sensors were met by all of the tested sensors; however, the more stringent ±0.5 percent manufacturing specification for conductance was not met by the sensors during the extended temperature testing. The pH sensors met the USGS criteria at pH 4 through pH 12.45, but exceeded the allowable deviation at pH 1.68. Detection range for the EXO turbidity sensors was determined to be suppressed when the sensors were tested in StablCal and formazin standards; however, the turbidity sensors met the USGS criteria when tested in AMCO–AEPA standards. The results from the field deployment indicated acceptable agreement in temperature, specific conductance, pH, and DO between the EXO sondes and the Hydrolab DataSonde 5X site sonde, and between the EXOs and the YSI 6920 V2-2 reference sonde. The EXO1 and EXO2 turbidity measurements differed from the Hydrolab DataSonde 5X approximately 23 and 25 percent, respectively.

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Figure 1. The EXO1 (left) and EXO2 (right) are shown with accessories.

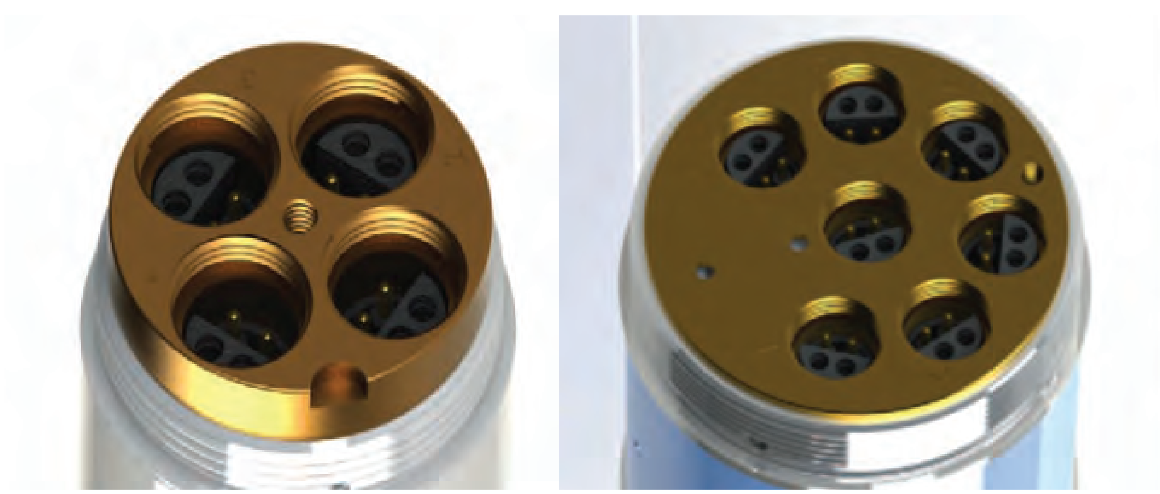

Figure 2. The four sensor ports of the EXO1 (left) and the seven sensor ports of the EXO2 (right). The center port on the EXO2 is used specifically for the optional central wiper.

Figure 3. The top of an EXO2. Shown in the figure is the cable connector (top left), battery valve (bottom center), and expansion port for a third party sensor (top right).

Figure 4. Data collection platform signal output adapter for RS–232 or serial data interface (SDI–12) data logger applications.

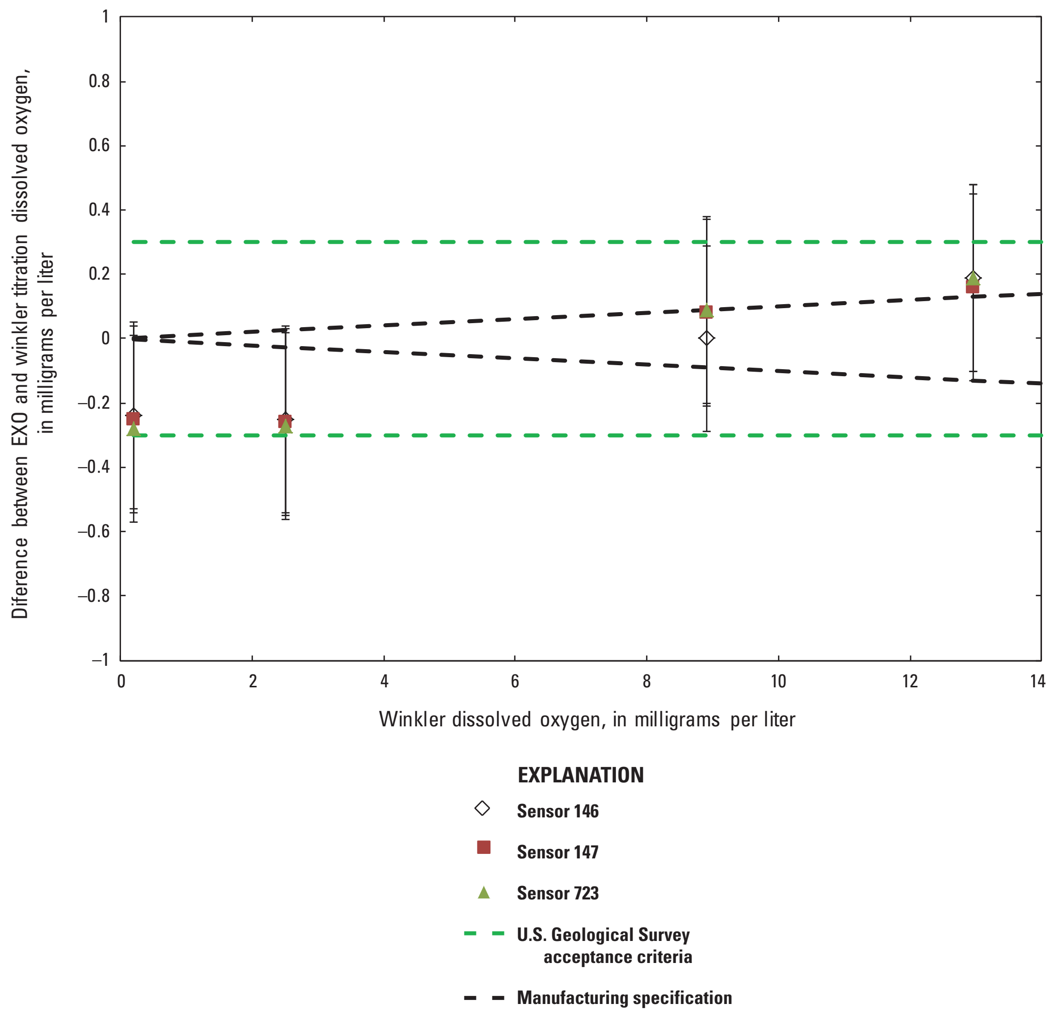

Figure 5. Differences between EXO dissolved oxygen sensor measurements and independently analyzed Winkler titrations. Green dashed lines represent the ±0.3 milligram per liter U.S. Geological Survey acceptance criteria, and black dashed lines represent the manufacturing specification of ±1 percent.

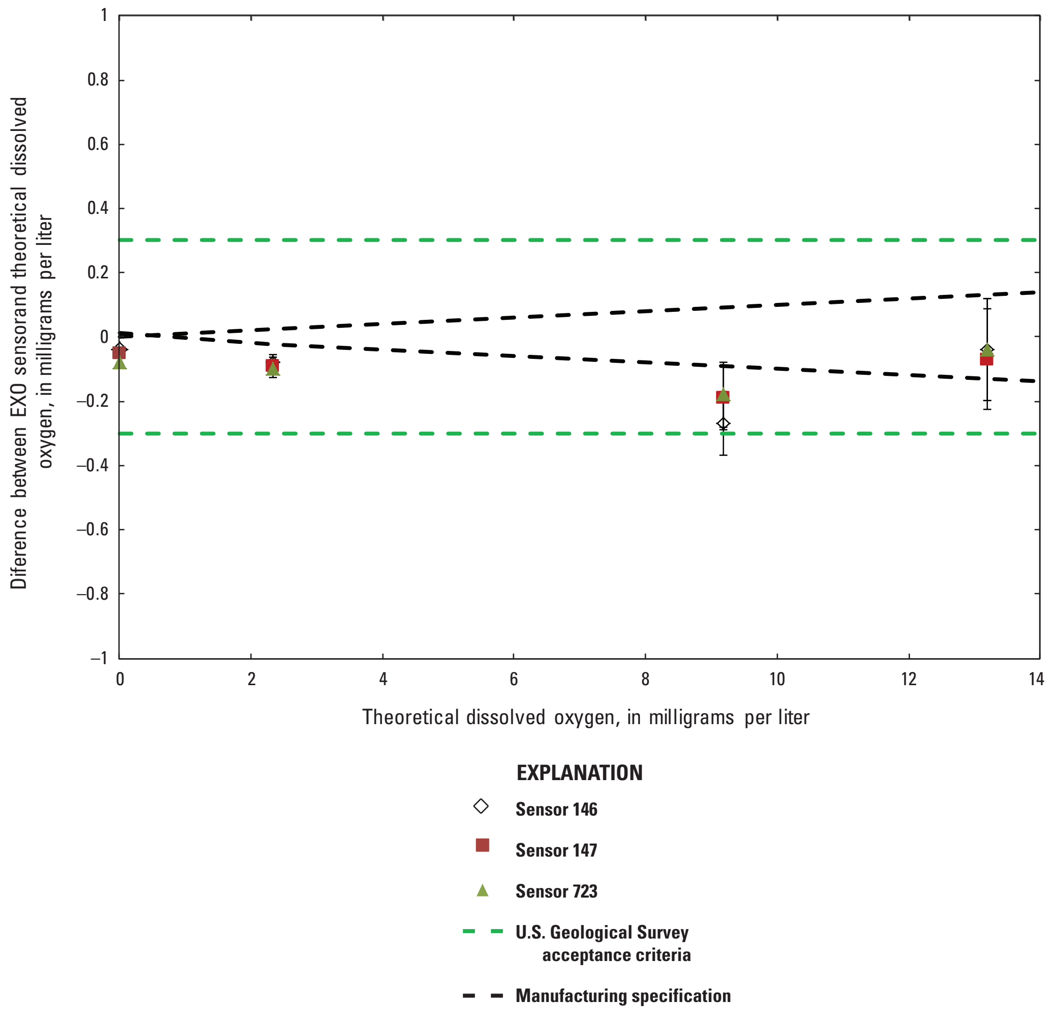

Figure 6. Differences between EXO dissolved oxygen sensor measurements and theoretical dissolved oxygen concentrations. Green dashed lines represent the ±0.3 milligram per liter U.S. Geological Survey acceptance criteria, and the black dashed lines represent the manufacturing specification of ±1 percent.

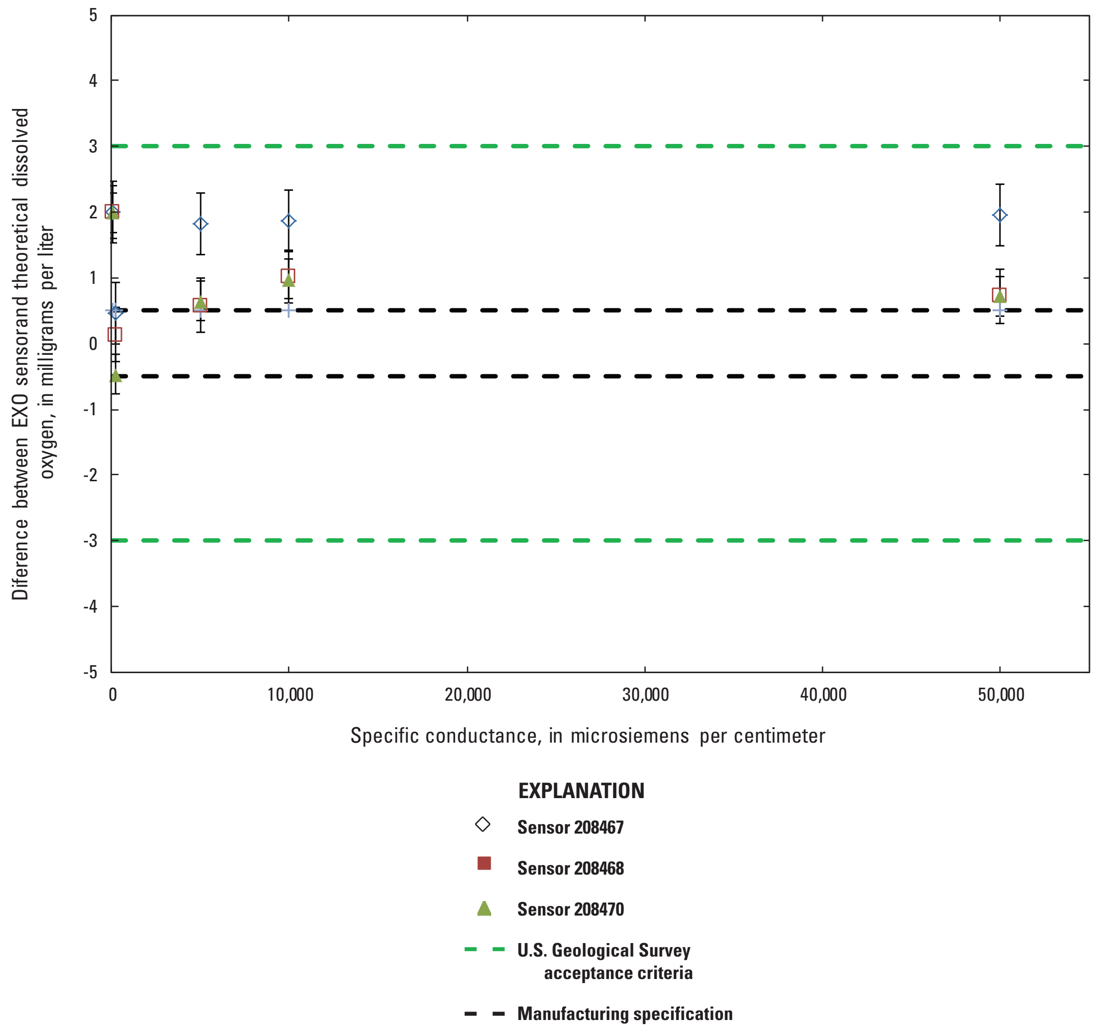

Figure 7. Percent differences between EXO conductivity/temperature sensor measurements and National Institute of Standards and Technology traceable standards in specific conductances of 50; 250; 5,000; 10,000; and 50,000 µS/cm at room temperature. Green dashed lines represent the ±3 percent U.S. Geological Survey acceptance criteria, and the black dashed lines represent the manufacturing specification of ±0.5 percent. Vertical error bars represent the largest uncertainty from the standards' certificates of analysis.

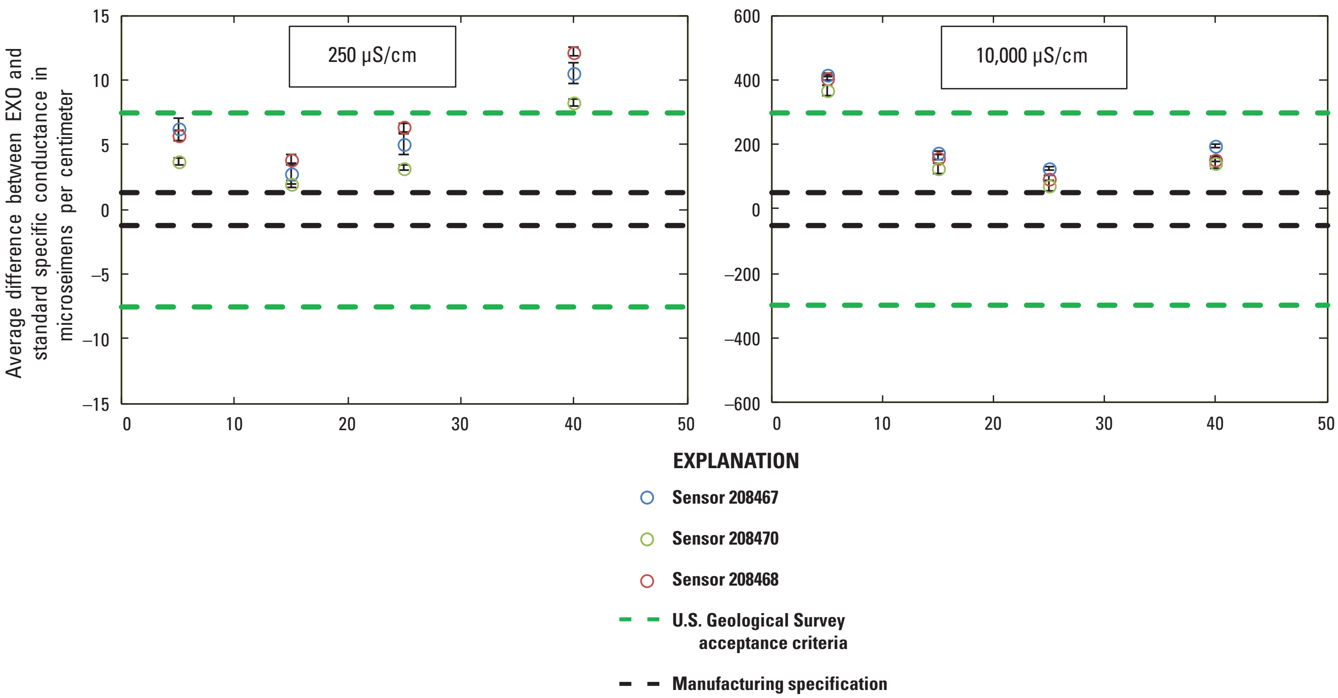

Figure 8. Mean measured to standard difference between three EXO conductivity sensors' specific conductance and two reference standards (250 µS/cm (left) and 10,000 µS/cm standard (right)) at 5, 15, 25, and 40 °C. Standard uncertainty is represented by the vertical error bars. Green dashed lines represent the ±3 percent U.S. Geological Survey acceptance criteria, and the black dashed lines represent the manufacturing specification of ±0.5 percent.

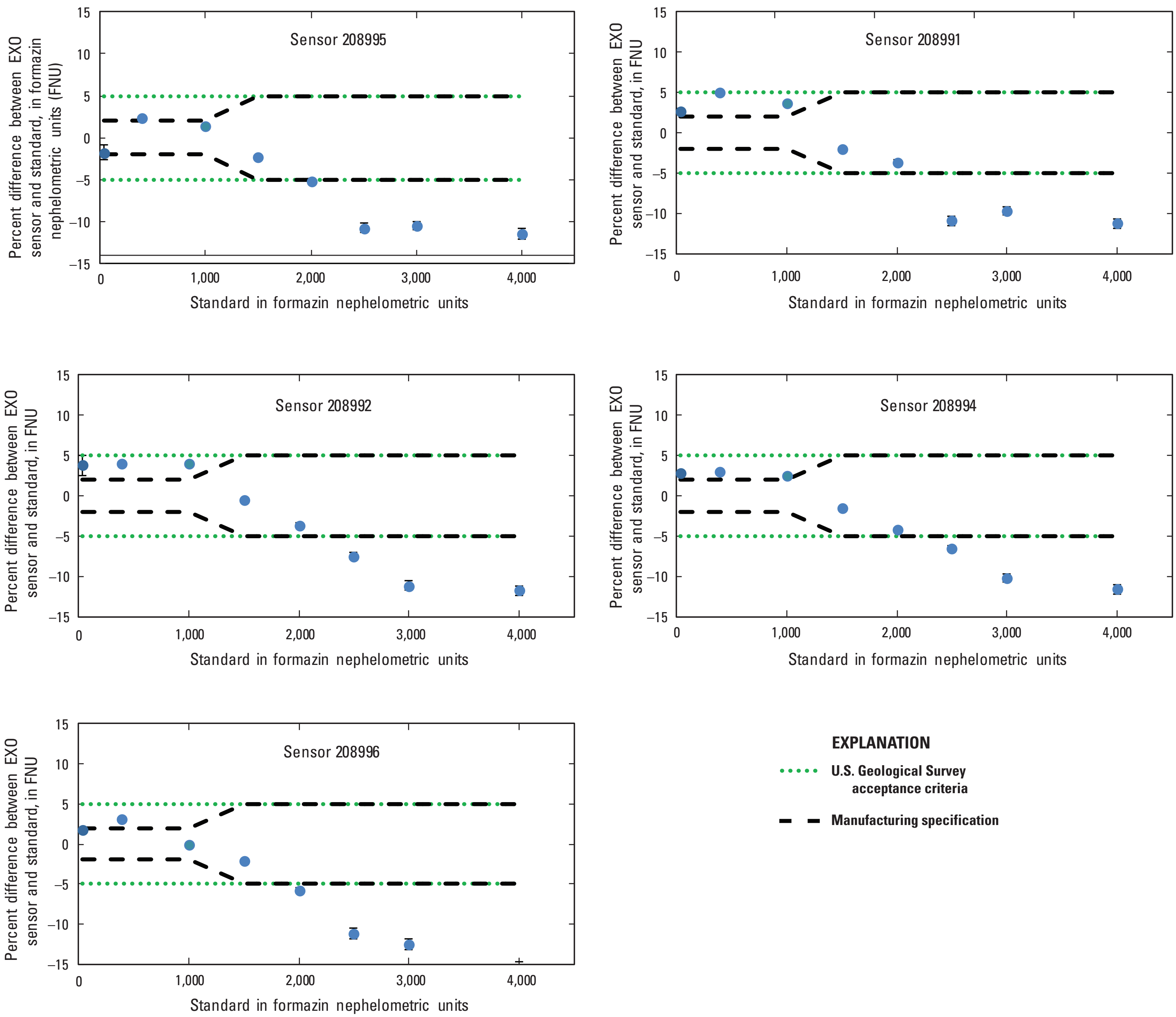

Figure 9. Average percent differences between the EXO turbidity sensor measurements and StablCal turbidity standards. Vertical error bars represent the expanded uncertainty at 95-percent confidence. The green dotted lines represent the ±5 percent U.S. Geological Survey acceptance criteria, and the black dashed lines represent the manufacturing specifications of ±2 and ±5 percent.

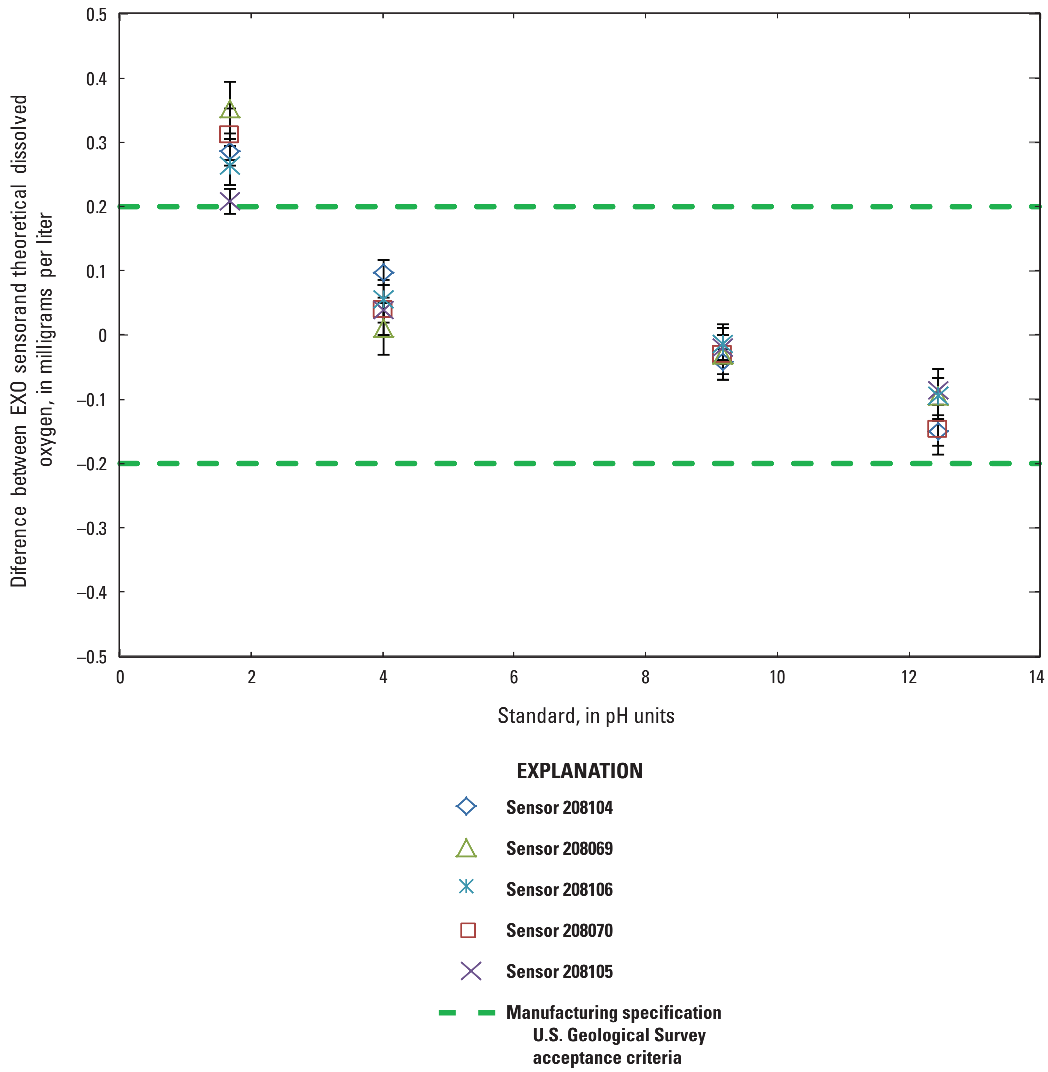

Figure 10. Difference between the mean pH measurements and the pH standard at room temperature. Five measurements were collected for each pH standard, and the mean was calculated and compared to the standard value. Green dashed lines represent the ±0.2 pH unit manufacturing specification and the U.S. Geological Survey criteria.

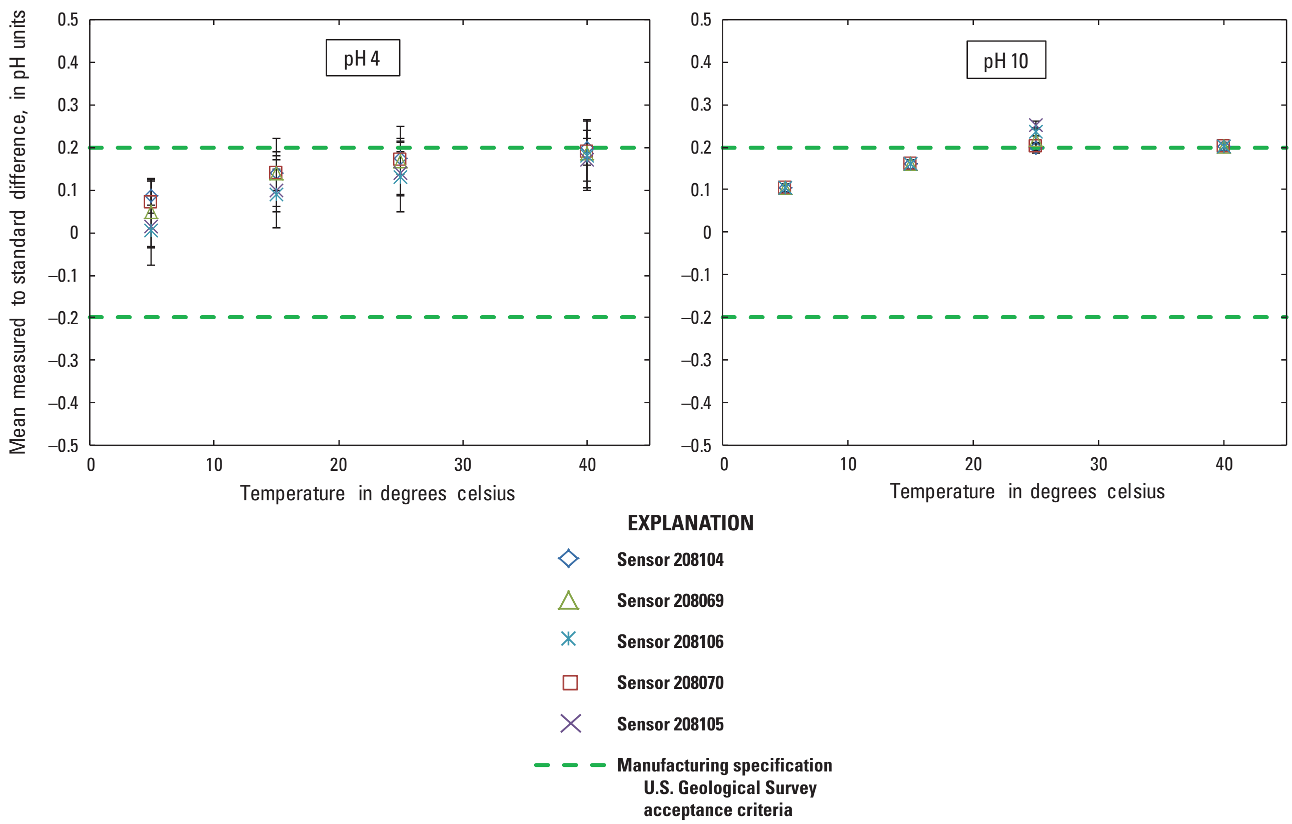

Figure 11. Mean differences between the EXO pH sensor measurements and the standard value in two standards: pH 4 and pH 10 at 5, 15, 25, and 40 °C. Five replicates were averaged, and compared to the reference standard value at each target temperature. Vertical error bars represent the maximum standard error across the temperature range. Green dashed lines represent the ±0.2 pH unit U.S. Geological Survey criteria.

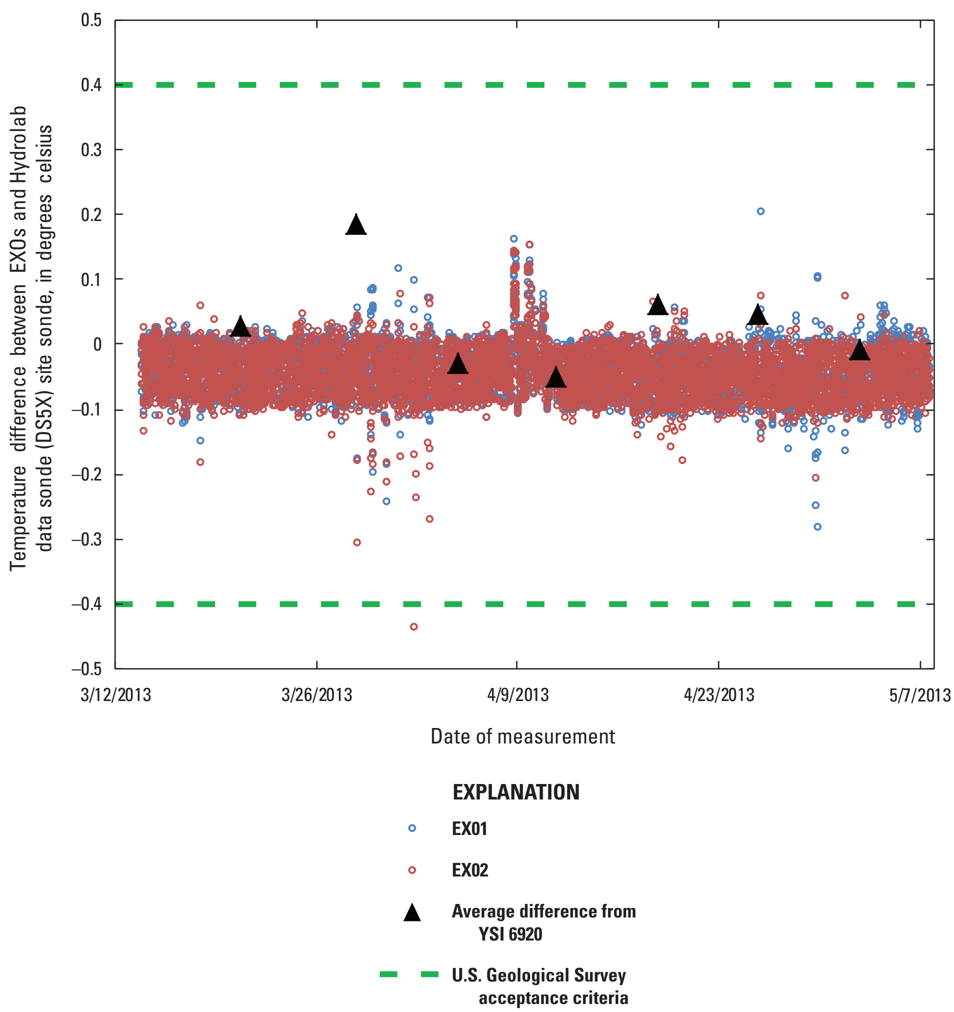

Figure 12. Differences between the measured temperatures of the EXOs and the Hydrolab DataSonde 5X site sonde. The green dashed lines represent the ±0.4 degree Celsius U.S. Geological Survey acceptance criteria established for the test, and the black diamonds represent the average difference between the EXOs and the YSI 6920 reference sonde.

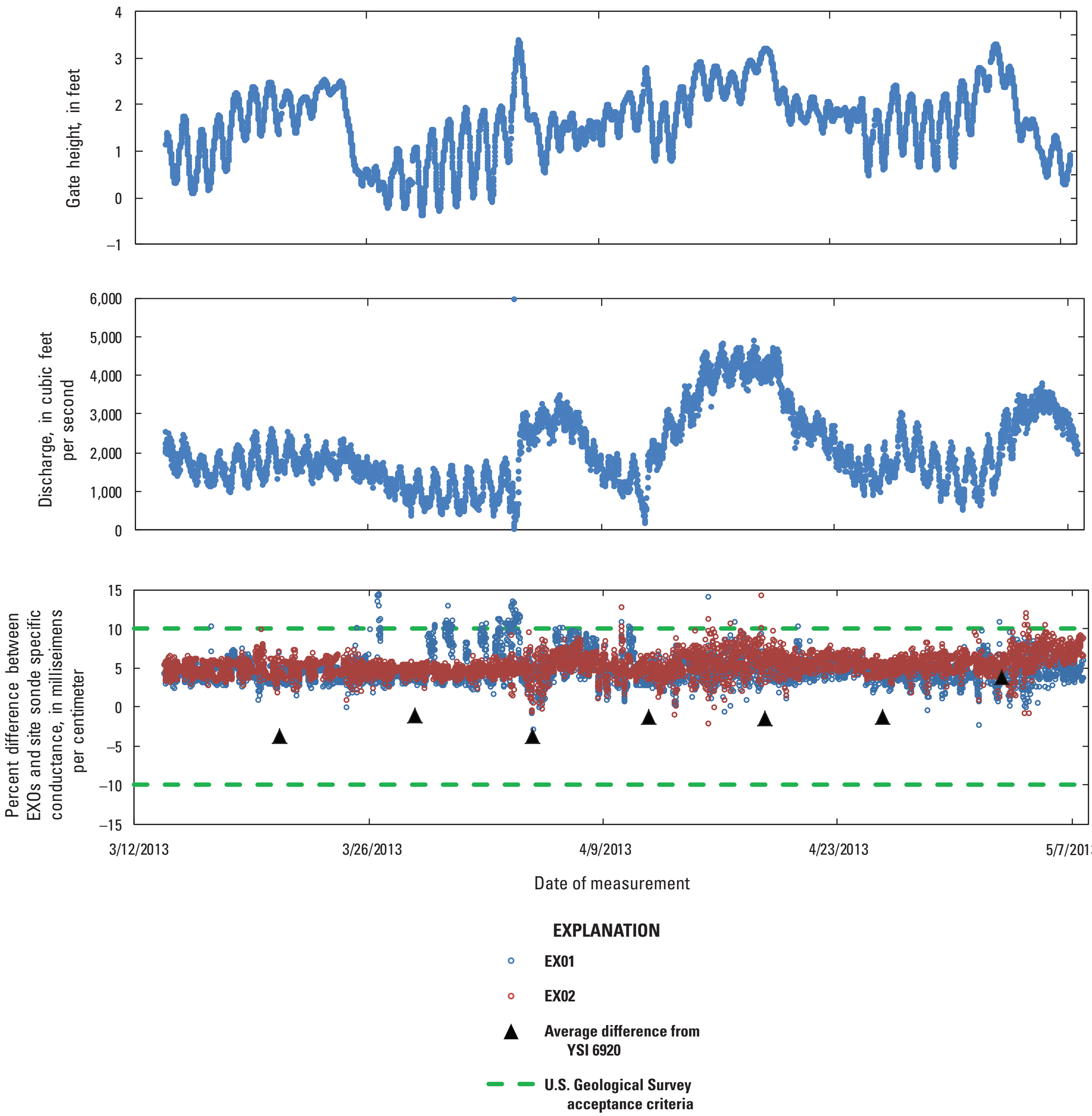

Figure 13. Differences between the measured specific conductance of the EXOs and the Hydrolab DataSonde 5X site sonde plotted with stage and discharge. The green dashed lines represent the ±10 percent U.S. Geological Survey acceptance criteria established for the test, and the black diamonds represent the average difference between the EXOs and the YSI 6920 reference sonde.

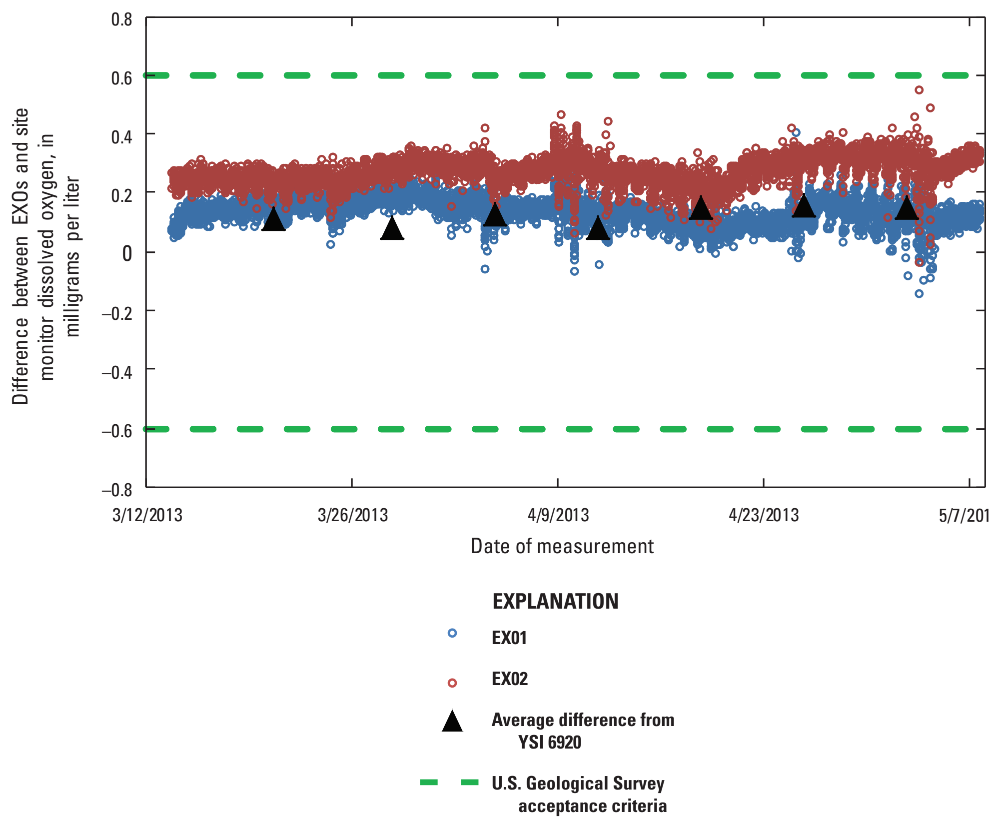

Figure 14. Differences in dissolved oxygen between the EXO sondes and the Hydrolab DataSonde 5X site sonde. The green dashed lines represent the ±0.6 milligram per liter evaluation U.S. Geological Survey acceptance criteria, and the black diamonds represent the average difference between the EXOs and the YSI 6920 reference sonde.

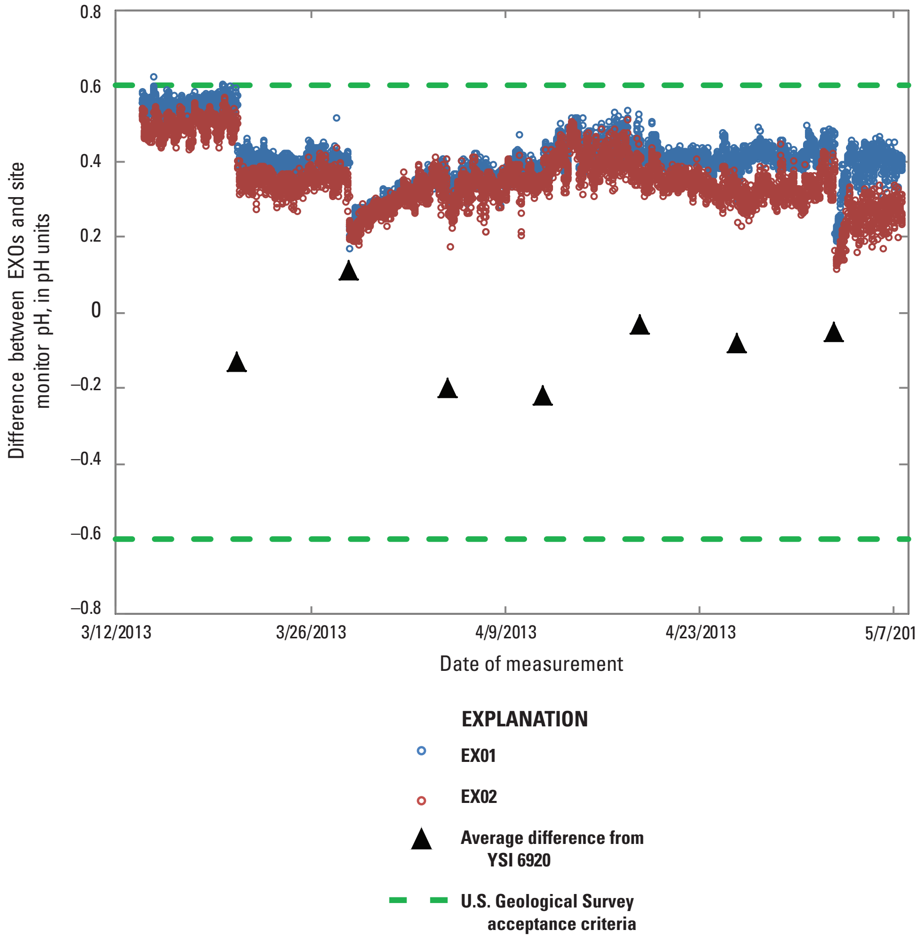

Figure 15. Differences in pH between the EXO sondes and the Hydrolab DataSonde 5X site sonde. The green dashed lines represent the ±0.6 pH unit evaluation U.S. Geological Survey acceptance criteria, and the black diamonds represent the average difference between the EXOs and the YSI 6920 V2-2 reference sonde.

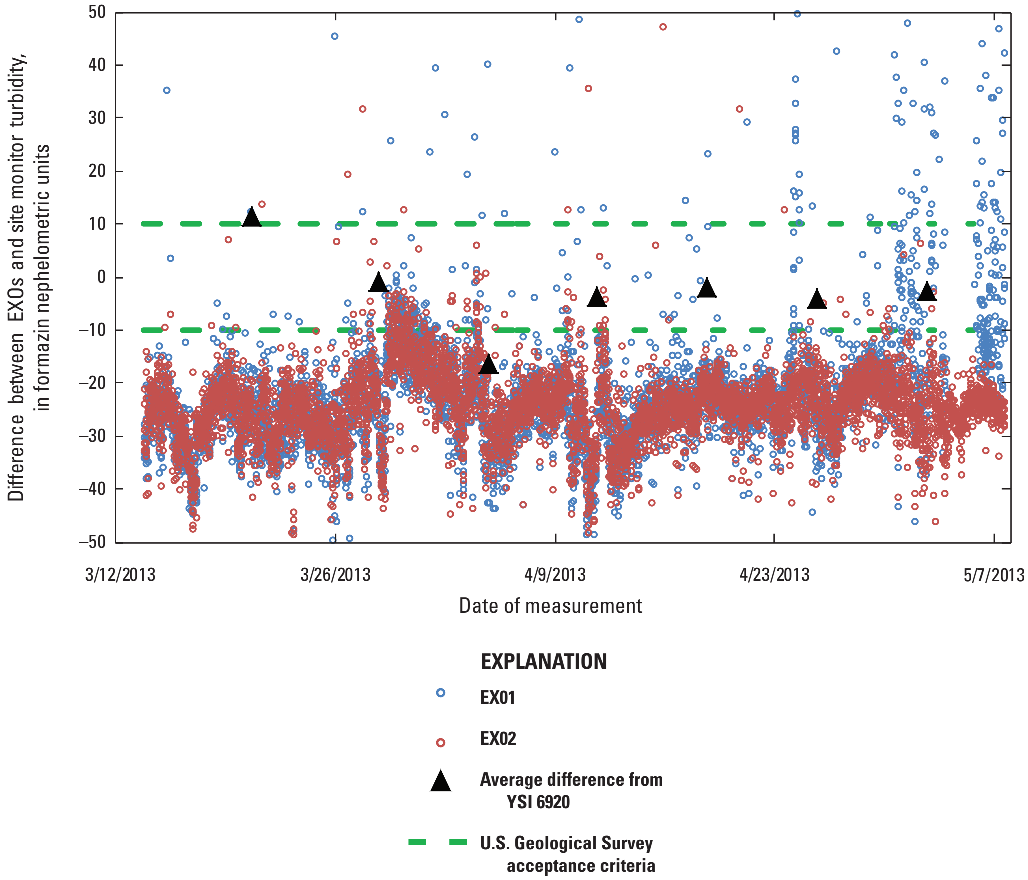

Figure 16. Differences in turbidity between the EXO sondes and the Hydrolab DataSonde 5X site sonde. The green dotted lines represent the ±10 percent U.S. Geological Survey evaluation acceptance criteria, and the black diamonds represent the average difference between the EXOs and the YSI 6920 V2-2 reference sonde.

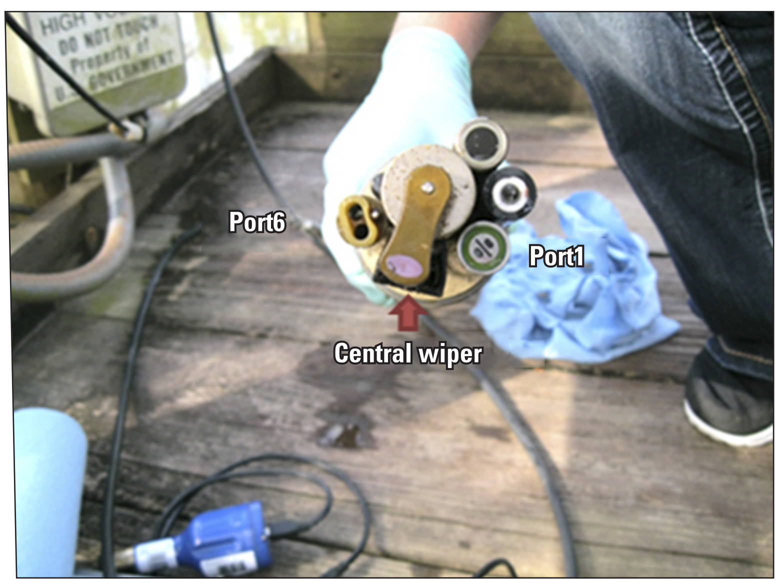

Figure 17. A photograph showing the sensor port assignment in relation to the central wiper of the EXO2 sonde.

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