EXO Water Quality Field Sensors:

Features, Specifications, and Comparability to YSI 6-Series Sensors

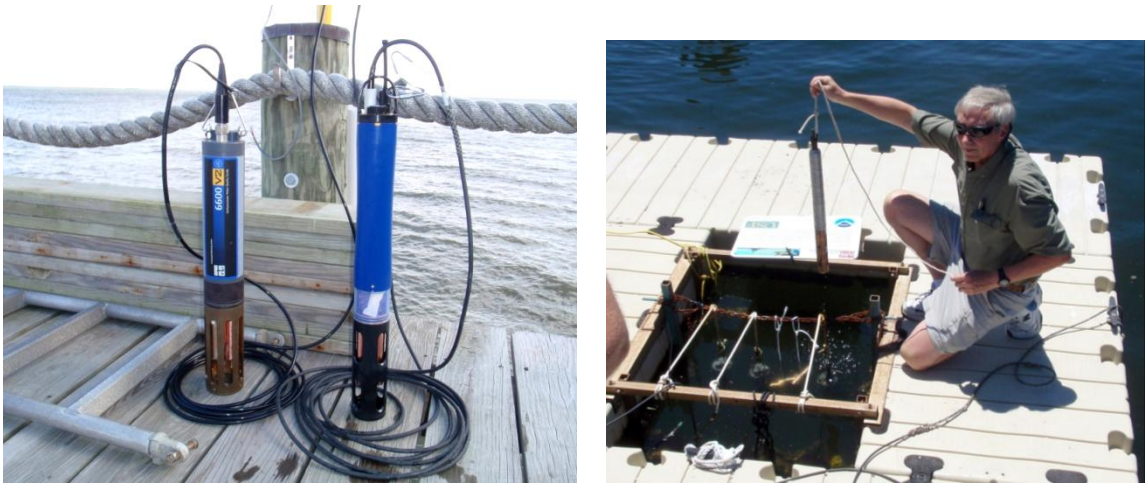
Introduction

The EXO multiparameter water quality sonde product line includes nine sensors that detect a variety of physical, chemical, and biological properties of natural water. The product line is designed to collect highly accurate data under ever-changing environmental conditions and water matrices. The two main sonde applications are; 1) long-term monitoring where maintenance intervals are typically longer than 1 month and biofouling, sensor stability, and system durability are principal concerns and 2) sampling requiring fast response for rapid data collection in often vastly different water qualities. Each EXO sensor employs a distinct sensing technology with specific performance and behavior in natural environments. A basic understanding of the sensing technologies and possible interferences encountered in natural environments will allow the user to improve deployment strategies, interpret data, and improve data quality.

EXO represents a new generation of water quality monitoring instruments from YSI, and a great deal of attention has been committed to assuring that a transition from YSI 6-Series to EXO products does not introduce discontinuities or disruptions into long-term data sets that have been developed with the 6-Series. The YSI 6-Series product line includes a broad number of sonde models, sensors and accessories that have been in production since the early 1990s, with tens of thousands of products sold and in use globally.

The field sensor market has developed rapidly over the past 30 years and, due to the relatively young age of the applications and the challenges presented from sensing in uncontrolled natural environments, there are few industry standards in place to assure consistency in field sensor data. This presents a challenge to the community because ‘identical’ sensors produced by different manufacturers will be built using different components and designs. This product variability is often ‘calibrated out’ using primary standards under controlled laboratory conditions. However, under variable field conditions, data inconsistency is often observed.

This white paper presents information and comparison data between the 6-Series and EXO sensors under a variety of field and laboratory conditions. We believe we have succeeded in developing new instruments that can be successfully ‘dropped in’ to existing monitoring programs and provide consistent data to the 6-Series with the benefit of many performance improvements. In some cases there will be a slight difference in an EXO and 6-Series sensor. In these instances data will be presented that will characterize this change under various environmental conditions. However, users are encouraged to conduct their own side-by-side studies with the 6-Series and EXO in their specific environments of interest to obtain the most accurate data comparison.



Long-term side-by-side studies comparing water quality data collected by EXO and 6-Series sondes in variable field conditions.

Sensor Platform

All EXO sensors are digital sensors with on-board signal processing and memory. This digital platform offers many advantages to the user including:

- Improved detection limits and response times due to analog-to-digital electronics contained close to sensing element, resulting in cleaner signals, reduced interference, and faster signal processing.
- Auto-recognition of sensors by the sonde, eliminating potential for user errors.
- Sensor diagnostics, metadata and calibration data stored in sensors, allowing for calibration in one sonde and transfer to other sondes.

Each EXO sensor has an on-board thermistor that is used for temperature compensation and can also be used as a back-up thermistor in the event that the EXO CT sensor is damaged or is missing. Because the sensor ports on EXO sondes are identical, users have the ability to calibrate multiple of the same sensor type in one sonde and then distributing calibrated sensors to other sondes, saving valuable time and money on calibration standards.

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Temperature

The EXO temperature sensor is significantly more accurate (+/- 0.01 C) than the 6-Series temperature sensor (+/- 0.15 C). All sensors undergo an extensive calibration process in a series of temperature baths at YSI's metrology laboratory and ship with a NIST-traceable calibration certificate. This greater accuracy will be particularly important in studies where water shows minimal temperature change (e.g., oceanographic applications), but will be a benefit to all sampling and monitoring studies. The minimal discontinuities that you would observe on transition between EXO and 6-Series systems would only reflect the greater accuracy of the EXO sensor. The EXO sensor is also much faster (ca. 3x) in response than the 6-Series sensor and this should be a significant benefit in sampling and profiling (horizontal and vertical).

TEMPERATURE	EXO	6-Series
Range	-5 to 50°C	-5 to 60°C
Accuracy	±0.01 °C (-5 to 35°C) ±0.05 °C (35 to 50°C)	±0.15 °C
Response Time	T63<1 sec	NA

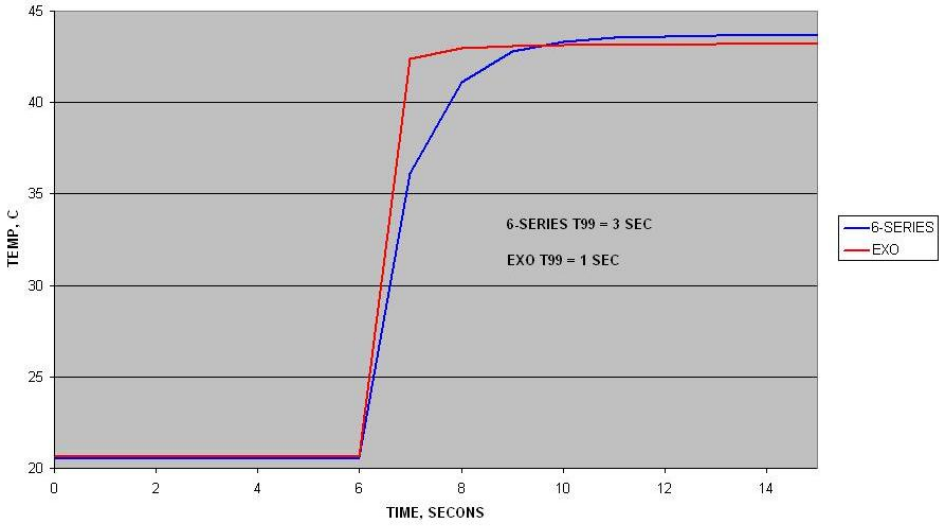

Figure 1: Comparison of response time between EXO and 6-Series temperature sensors. Transfer from ambient temperature water to hot water with rapid stirring.

Conductivity

The EXO conductivity sensor works with the same proven cell design and circuitry as that used in the 6-Series conductivity sensor. Thus, the accuracy of the EXO sensor will be identical to that of the 6-Series sensor (+/- 0.5% of the reading or 1 uS/cm) and no discontinuities should be observed on transition from one system to the other. The range of the EXO sensor is greater (200 mS/cm) than that for the 6-series sensor (100 mS/cm), which will be useful for very high conductivity applications such as studies in hypersaline environments. The response times for the EXO and 6-Series conductivity sensors are both effectively instantaneous in their raw responses and any differences would be due to user-selectable data filters where some speed of response might be compromised in order to obtain readings which are more stable. However, the readings of both systems are very stable with minimal filtering while maintaining a very fast response.

The conductivity cell mechanical design has been improved to facilitate flushing and prevent bubble entrainment. The mechanical design and materials have also been improved to increase durability and sensor longevity. The EXO CT sensor is constructed using titanium sensor and thermistor housings, an extremely durable and stable glass-filled Ultem epoxy with a very low CTE, and a wet-mate connector.

CONDUCTIVITY	EXO	6-Series
Range	0-200 mS/cm	0-100 mS/cm
Accuracy	±0.5% or reading or 0.001 mS/cm w.i.g.(0-100 mS/cm) ±1% or reading (100-200 mS/cm)	±0.5% or reading or 0.001 mS/cm w.i.g.
Response Time	T63<2 sec	NA

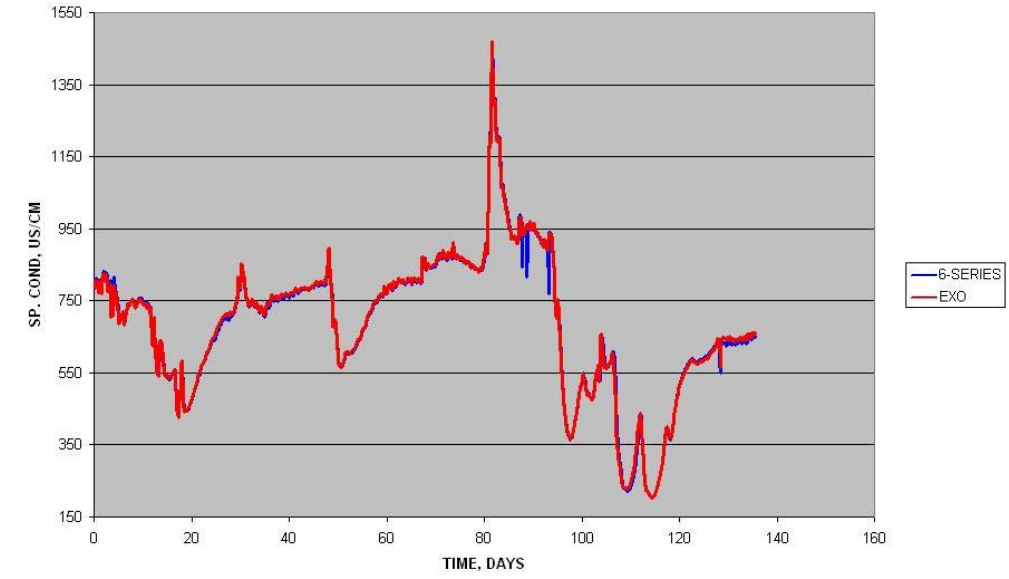

Figure 2: Comparison of specific conductance between EXO and 6-Series in Miami River, OH over 140 days.

Dissolved Oxygen

The optical dissolved oxygen sensor available with the EXO system will show the same excellent accuracy (+/- 1% of the reading or 1% air-saturation) and stability for most applications (0-200% air-saturation; 0-20 mg/L) as the ROX sensor available on the 6-Series system. However, the EXO dissolved sensor shows significantly greater accuracy (+/- 5% of the reading) than the ROX sensor (+/- 15% of the reading) in the 200-500% air-saturation range (20-50 mg/L), so the EXO sensor will have an advantage in applications involving high biological productivity. The EXO sensor also is more accurate at depths greater than 30 m (100 feet) than the corresponding ROX sensor. In addition, the EXO sensor will have a response time which is approximately half that of the ROX sensor and this factor will be a significant advantage in profiling and sampling studies. Overall, for most applications, users will see no difference in accuracy and stability in monitoring studies on transition between 6-Series and EXO systems, but the greater accuracy at high oxygen levels and the faster response time will be significant advantages.

The EXO ODO sensor is constructed with titanium with a wet-mate connector. The membrane cap includes titanium, sapphire glass, and proprietary ODO membrane materials.

OPTICAL DO	EXO	6-Series
Range	0-500%, 0-50 mg/L	0-500%, 0-50 mg/L
Accuracy	±1%, ±0.1 mg/L (0- 20 mg/L) ±5% (20-50 mg/L)	±1%, ±0.1 mg/L (0-20 mg/L) ±15%, ±1.5 mg/L (20-50 mg/L)
Response Time	T63<5 sec	NA

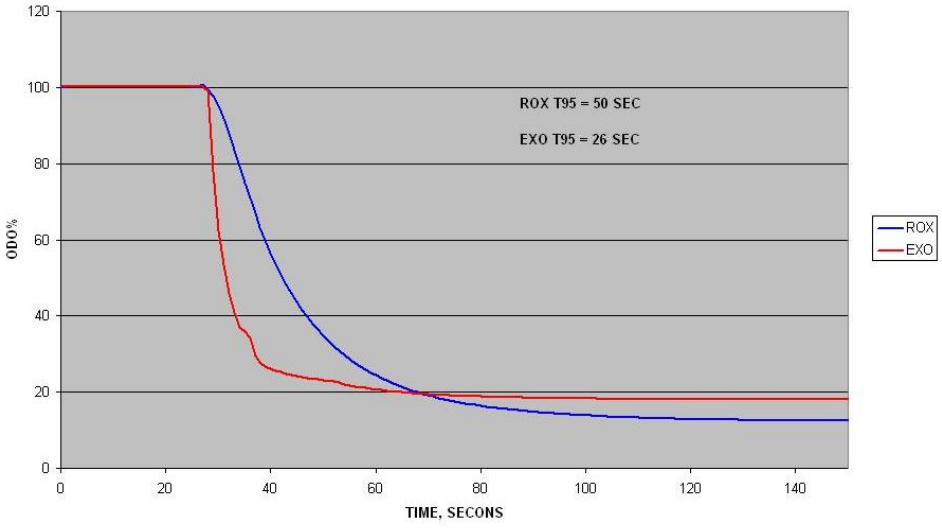

Figure 3: Comparison of response times between the 6-Series ROX DO sensor and the EXO Optical Dissolved Oxygen Sensor. Transfer from air-saturated water to deaerated water with rapid stirring.

pH

The EXO pH sensor works with basically the same design and circuitry as used in 6-Series pH sensors with a preamplifier device (e.g., the 6589), but is specified for better accuracy (+/- 0.1 pH unit) when the sensor is calibrated within +/- 10°C of the water being monitored. While the response time for the EXO sensor is equivalent to that of a new 6589 6-Series sensor under most conditions, it is anticipated that the design of the EXO sensor will allow this fast response to be maintained while the response of the 6-Series sensor will become slower as it ages. In addition, the preamplifier design of the EXO sensor will make it less susceptible to electrical interference during calibration than the older 6-Series pH sensors. Finally, the pH sensor will automatically be mechanically cleaned in EXO2 deployments without the use of any special wipers, etc. In general, you should see no significant discontinuity on changing from a 6-Series to an EXO pH sensor with a longer product lifecycle, improved biofouling protection and lower cost of ownership.

The EXO pH sensor base is constructed with titanium with a wet-mate connector.

pH	EXO	6-Series
Range	0-14 units	0-14 units
Accuracy	±0.1 units (within ±10°C of cal temp) ±0.2 units for entire temperature range	±0.2 units
Response Time	T63<3 sec	NA

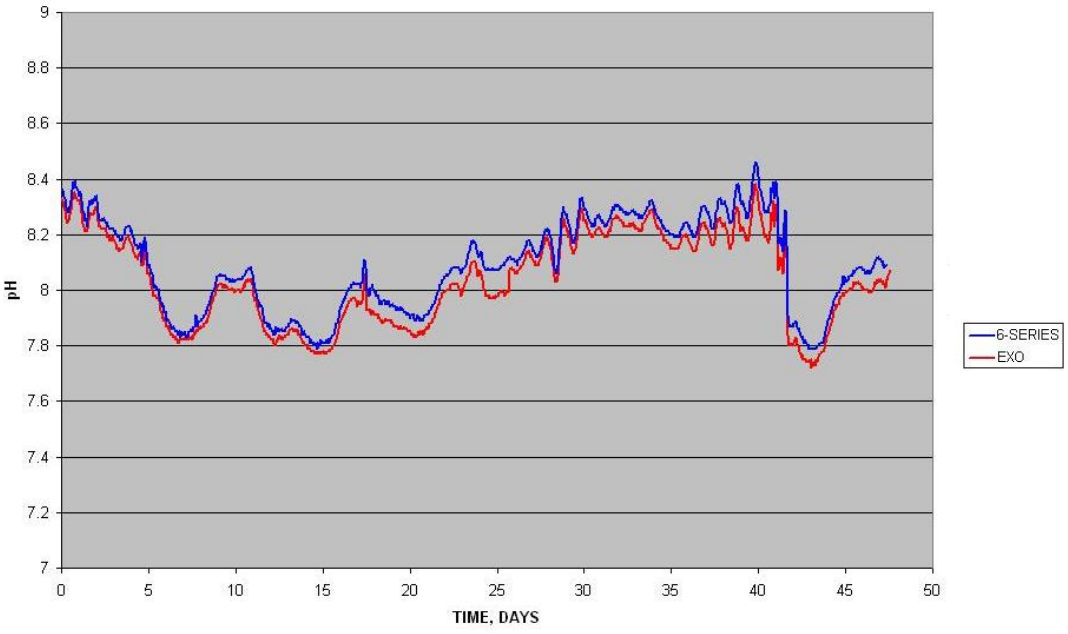

Figure 4: Comparison of pH for EXO and 6-Series pH sensors over 48-day deployment in Miami River, OH.

ORP

The EXO ORP sensor will show equivalent accuracy and stability as the ORP sensor for the 6-Series system. The EXO sensor may have a slightly faster response in environmental and process water applications, but this effect will likely be small. In addition, the EXO ORP sensor will automatically be mechanically cleaned in EXO2 deployments without the use of any special wipers, etc. Overall, you should see no significant discontinuity on transition between ORP sensors in EXO and 6-series systems.

ORP	EXO	6-Series
Range	-999 to +999 mV	-999 to +999 mV
Accuracy	+/-20 mV in redox standard solutions	+/-20 mV in redox standard solutions
Response Time	T63<5 sec	NA

Turbidity

The EXO turbidity sensor works on the same principle as the sensor used in 6-Series systems and thus will show approximately the same accuracy and stability in standards and in environmental water. The response times for the EXO and 6-Series turbidity sensors are both effectively instantaneous in their raw responses and any differences would be due to user-selectable data filters where some speed of response might be compromised in order to obtain readings which are more stable. However, the readings of both systems are very stable with minimal filtering while maintaining a very fast response.

The major advantage of the EXO sensor is that it will read up to 4000 NTU (or FNU) as opposed to the 6-Series, which has a 1000 NTU limit.

Since the optics of the EXO turbidity sensor is slightly different from those in the 6-Series system, it is likely that there will be a slight discontinuity in field readings taken with the two systems after calibration in the same laboratory standard. For example, differences in sediment readings of up to 10% at the same site are possible when transitioning between the 6-Series and EXO sensors with the EXO readings generally being lower in value. For users who are concerned about this difference, YSI will be able to provide support in rationalizing historical 6-Series data to EXO data with minimal effort in the process. In addition, the slightly different optics of the EXO sensor will result in a different calibration value for the YSI midrange AEPA-AMCO standard (126 NTU for the 6136 and now 125 NTU for EXO) which is used by a majority of YSI customers.

The EXO turbidity sensor is constructed with titanium with a sapphire glass window and wet-mate connector.

TURBIDITY	EXO	6-Series
Range	0-4000 FNU	0-1000 FNU
Accuracy	0.3 FNU or ±2% or reading w.i.g. (0-1000 FNU) ±5% or reading (1000-4000 FNU)	0.3 FNU or ±2% or reading w.i.g.
Response Time	T63<2 sec	NA

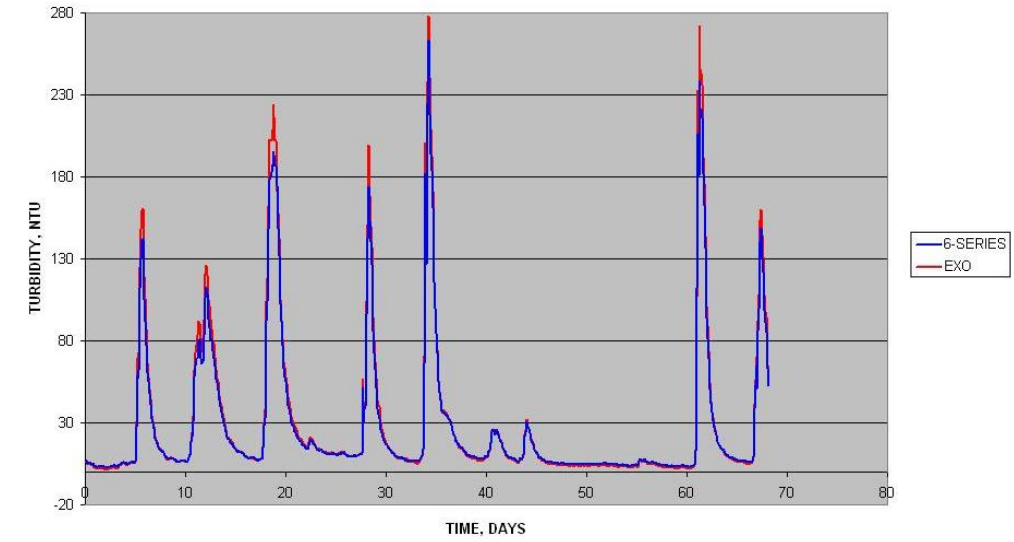

Figure 5: Comparison of turbidity sensors between 6-Series and EXO over a 68-day deployment at Miami River, OH.

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Total Algae - Chlorophyll

The chlorophyll sensor for the EXO system is one component of the Total Algae probe which also contains a blue-green algae (cyanobacteria) sensor. The EXO chlorophyll sensor operates on the same *in vivo* fluorescence principle as the 6-Series sensor with no disruption of the cells required to obtain either spot readings or long-term monitoring data. The EXO sensor has a better detection limit than the 6-Series sensor as determined under laboratory conditions, and this advantage should be realized in many field applications. Like the 6-Series chlorophyll sensor, the EXO readings show excellent linearity on serial dilution of a surrogate solution of Rhodamine WT ($R^2 > 0.9998$) and this should ensure relative accuracy of field chlorophyll readings, i.e., a chlorophyll reading of 100 units will represent twice the algal content of water with a chlorophyll reading of 50 units.

It is not possible to specify accuracy for chlorophyll and blue-green algae sensors due to the variability of *in vivo* fluorescence from species to species, the effect of particle size and temperature on the sensor output, and the effect of ambient light on photosynthesis, which can also vary depending on deployment conditions and species variability. Also, like the 6-Series sensor, in order to obtain the best possible agreement between sensor readings and those obtained after cell disruption and extraction of chlorophyll *a*, it will be necessary to actually calibrate the sensor in a medium of known algal chlorophyll content.

The biggest advantage of the EXO chlorophyll sensor over the 6-Series version is that the EXO readings show much less interference from turbidity and dissolved organics and this will allow for much more accurate determination of algal content under high turbidity conditions (i.e., a rainfall event) and in waters with high organic content (i.e., stained waters and in bottom waters). For example, users of the 6-Series system would typically see about 3 ug/L of chlorophyll interference in field water with a turbidity of 100 NTU, but only about 0.5 ug/L of chlorophyll interference for the EXO sensor under the same conditions. Overall the EXO sensor will show improved detection limits and response times, as good or better stability and lower noise levels as the current 6-Series sensor. The EXO sensor offers a big improvement in rejecting the interference from turbidity and dissolved organics, minimizing false positives and improving data accuracy.

The EXO total algae sensor is constructed with titanium with a sapphire glass window and wet-mate connector.

CHLOROPHYLL	EXO	6-Series
Range	0-400 ug/L Chl	0-400 ug/L
MDL	0.09 ug/L	0.5 ug/L
Response Time	T63<2 sec	NA

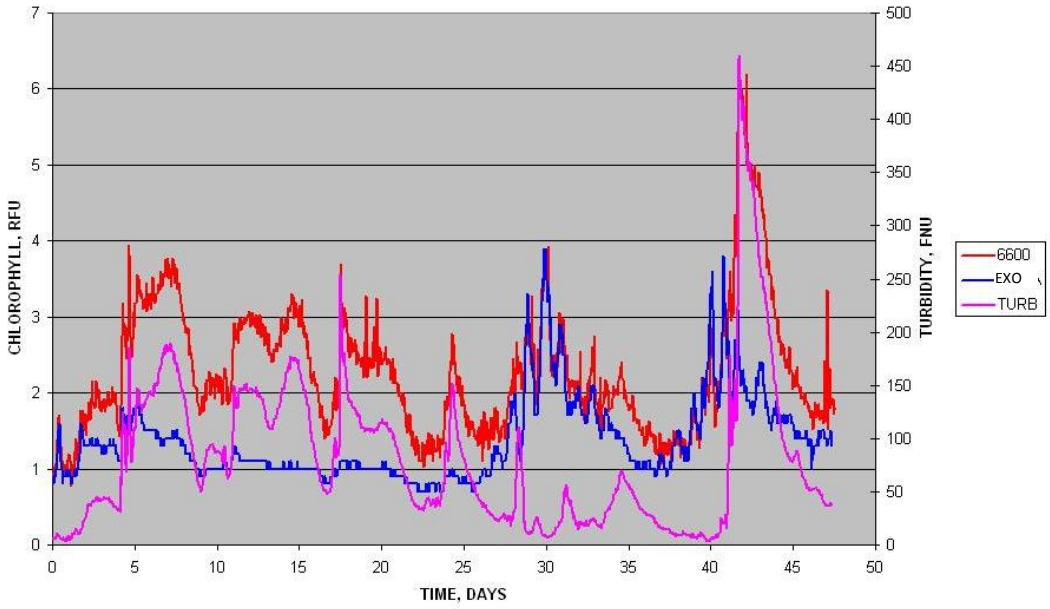

Figure 6: Comparison of chlorophyll sensors of EXO and 6-Series in Miami River, OH over 48-day deployment. The turbidity data demonstrates EXO's decreased sensitivity to turbidity interference from the 6-Series and other commercially available chlorophyll sensors.

Total Algae - BGA-PC

Similar to the chlorophyll sensor described above, the phycocyanin-based blue-green algae (BGA-PC) sensor for EXO is one component of the total algae probe. Like the 6-Series BGA-PC sensor, the EXO readings show excellent linearity on serial dilution of a surrogate solution of Rhodamine WT ($R^2 > 0.9997$) and this should ensure relative accuracy of field BGA-PC readings, i.e., a BGA-PC reading of 100 units will represent twice the algal content of water with a BGA-PC reading of 50 units. A significant advantage of the EXO BGA-PC sensor over the 6-Series version is that the EXO readings show less interference from turbidity and this will allow for much more accurate determination of BGA-PC content during rainfall events which release both sediment and algae into the water. For example, users of the 6-Series system would typically see about 1500 cells/mL of BGA-PC interference in field water with turbidity of 100 NTU, but only about half the interference for the EXO sensor under the same conditions.

A note on units: YSI no longer offer the cells/ml unit for BGA sensors. The relationship between fluorescent signal and cells/ml varies widely and use of the unit created confusion with customers and was often interpreted as a quantitative measure. Users who want data reported in cells/ml will need to determine the fluorescence:cells/ml relationship for an environment of interest and apply the correlation factor through a post-processing step. Units offered with include Relative Fluorescence Units (RFU), µg/L (estimate of phycocyanin pigment concentration), and the raw sensor output (RAW).

Overall the EXO sensor should show the same good stability as the current 6-Series sensor with lower detection limit, faster response time, and decreased sensitivity to turbidity and dissolved organic interference.

BGA PC	EXO	6-Series
Range	0-100 ug/L PC	0-200,000 cells/ml
MDL	0.04 ug/L	160 cells/ml
Response Time	T63<2 sec	NA

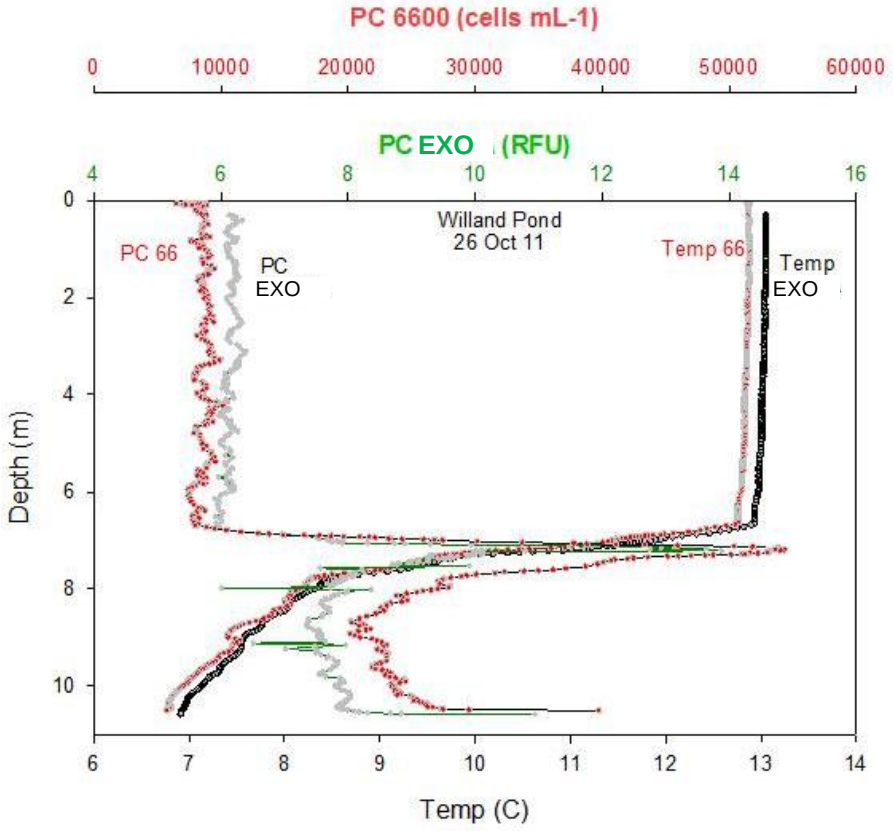

Figure 7: Comparison of blue-green algae (PC) sensors of EXO and 6-Series in vertical profile in Willand Pond, NH. Data shows faster response in the detecting sub-surface maxima and lower sensitivity to dissolved organic interference in region of high DOM below 7 m.

fDOM

The fDOM sensor which is offered for use with the EXO sondes has no real analogy in the 6-Series product line. (Note that it is possible to adapt a Turner Design CDOM Cyclops probe to the 6-Series platform with the loss of an optical port, but the sensor cannot be calibrated, is not mechanically cleaned, and thus is not comparable to the fDOM sensor manufactured for the EXO platform). The EXO fDOM sensor measures the fraction of dissolved organic matter (DOM) which fluoresces (f) when exposed to high-wavelength ultraviolet (UV) light (ca. 365 nm) and is comparable to other commercially available CDOM sensors but uses a more accurate naming convention. A surrogate for fDOM is quinine sulfate which, in acid solution, fluoresces similarly to dissolved organic matter. The units of fDOM and (usually) CDOM are "quinine sulfate units (QSUs)" where 1 QSU = 1 ppb quinine sulfate and thus quinine is really a "double surrogate" for the desired CDOM parameter. The EXO fDOM sensor shows virtually perfect linearity R^2 = 1.0000) on serial dilutions of a colorless solution of quinine sulfate. However, on serial dilution of stained water field samples, the sensor shows some underlinearity at levels above about 50 QSU due to the fact that the colored material in the water is absorbing some of the UV light and reducing its ability to produce fluorescence. This underlinearity is common to all commercially available CDOM sensors and the impact should be evaluated in your environment of study to properly interpret the data. The EXO fDOM sensors exhibits very low detection limits and fast response times.

The EXO fDOM sensor is constructed with titanium with a sapphire glass window and wet-mate connector.

fDOM	EXO	6-Series
Range	0-300 ppb QSE	NA
Accuracy	0.07 ppb QSE	NA
Response Time	T63<2 sec	NA

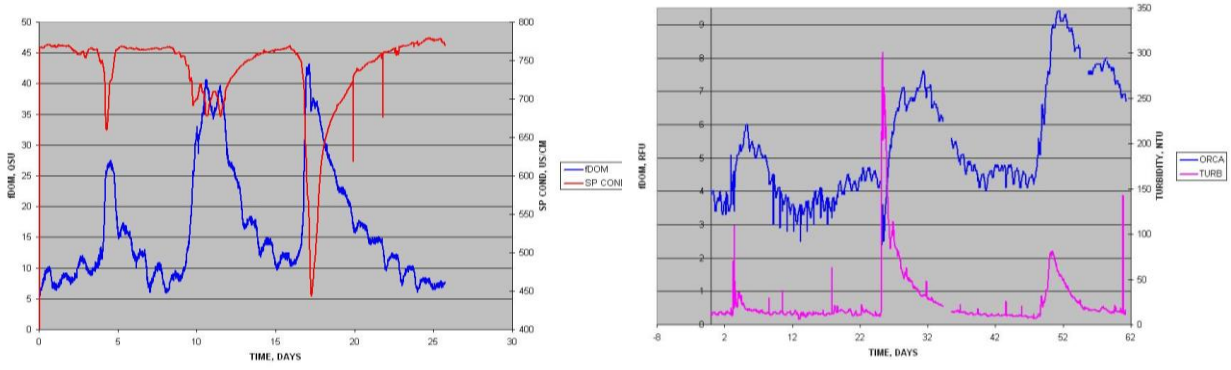

Figure 8: EXO fDOM sensor data from deployments in Miami River, OH. LEFT: fDOM data graphed with Specific Conductivity data to show the sensors' responses to rain events. RIGHT: fDOM data graphed with Turbidity data to show the sensors' responses to rain events

Depth and Level

The depth sensors (deep, medium, shallow, and shallow vented or level*) offered with the EXO sonde are strain gauge sensors, which are very similar in theory and performance to those offered with the 6-Series sondes. The sensors measure raw water pressure -- psi absolute (psia) for the non-vented sensors and psi gauge (psig) for the vented – which is then converted into a depth-of-water value using the temperature and salinity readings from the Conductivity/Temperature sensor. All EXO sensors exhibit improved accuracy to the 6-Series equivalent and this factor is their major advantage over the 6-Series. Also, there is a 250 m option on the EXO sondes, increasing the depth limits from the 6-Series.

DEPTH	EXO	6-Series
Range	0-10 m, 0-100 m, 0-250 m	0-9 m, 0-61 m, 0-200 m
Accuracy	±4.0 mm, ±4.0 cm, ±10.0 cm	±20.0 mm, ±12.0 cm, ±30.0 cm
Vented Accuracy (0-10 m)	±3.0 mm	±3.0 mm
Response Time	T63<2 sec	NA

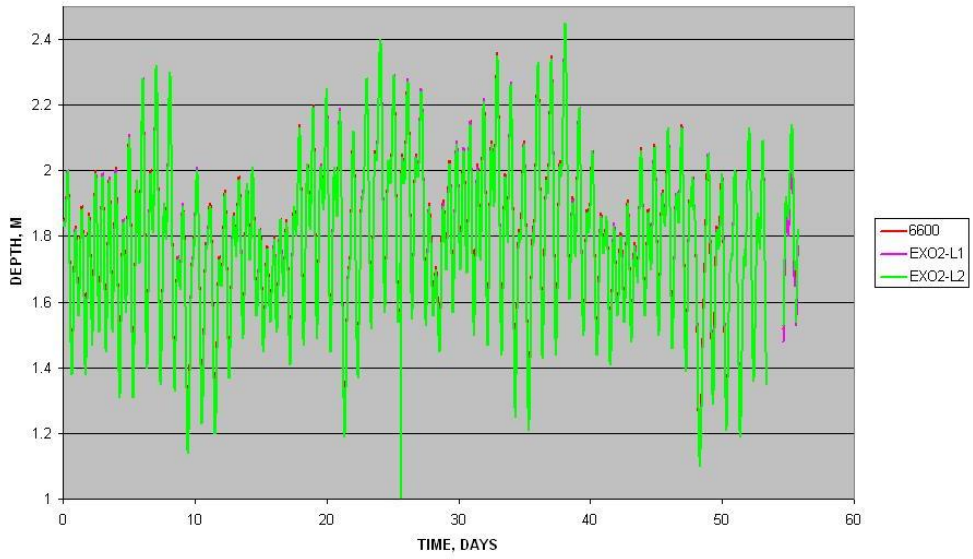

Figure 9: Comparison of depth data between 6-Series and two EXO sondes during a 57-day deployment monitoring tidal fluctuations in Tampa Bay, FL. Data shows excellent agreement between 6-Series and EXO.

*vented level is option available in 2013

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Conclusion

This report provides information and supporting data on the intercomparability of EXO and 6-Series sensors and is intended to provide existing 6-Series customers with information they need in order to move from the 6-Series to EXO product line. YSI is sensitive to the potential impact on data quality resulting from hardware changes and has focused on minimizing data inconsistencies between the 6-Series and EXO product lines. We have conducted multiple side-by-side field trials for over 18 months in a variety of freshwater, estuarine, and marine environments in an attempt to evaluate data from a variety of environments. However, every environment is unique and we encourage our customers to conduct their own side-by-side studies to determine inconsistencies between the product lines, if any, in their environments of study.

YSI technical support is available to answer questions, provide comparison data or assist our customers in any issues related to a transition from 6-Series to EXO product lines. Please feel free to contact us at environmental@ysi.com, +1 937-767-7241 or +1 800-765-4974 (US).

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