**Recommended Changes to Calibration Protocol for IMOS Backscatter and Turbidity Sensors**

**WG Recommendation**
IMOS scattering and turbidity sensors should be calibrated to SI units (m$^{-1}$), not nephelometric units (FTU/NTU).

**Introduction**
One objective of the IMOS National Working Group on Bio-optical Instrumentation and Observing ([http://imos.org.au/bwg.html](http://imos.org.au/bwg.html)) is to assess the calibration protocols for optical sensors utilised for IMOS deployments, so that a unified approach is taken to calibration of all nationally deployed optical sensors. A specific WG task was to recommend the most suitable approach for calibrating backscatter and turbidity sensors. This document outlines the Working Group’s recommendation for the most appropriate units with which to calibrate these sensors, and the associated scientific rationale.

**Definition of Turbidity and TSS**
"Turbidity is a property commonly used to describe water clarity in both marine and freshwater environments, providing a gross assessment of light attenuation due to the presence of suspended material. However, turbidity is often not a direct measure of the quantity of interest, such as suspended sediment, living particles, and nonliving organic matter, but rather a measure of the effect of the suspended particles on the optical properties of the water." (Boss et al. 2009)

The concentration of total suspended sediment (TSS, g m$^{-3}$) is a biogeochemical variable that links directly to water quality. TSS is determined gravimetrically from filtered water samples. In the water quality literature TSS is also referred to as suspended particulate matter concentration (SPM) or total suspended matter (TSM).

**Standard Methods for measuring Turbidity**
Turbidity is measured with turbidimeters that are calibrated in relative units of Nephelometric Turbidity Units (NTU), Formazine Turbidity Units (FTU) or Formazine Nephelometric Units (FNU) depending on which measurement standard they are designed to conform to. In the US, the standard relies on turbidimeters that measure the particle scattering of light from a tungsten lamp through a liquid medium, with the wavelength of the spectral peak response of the detection system between 400 and 600 nm (EPA method 180.1 ). Turbidimeters designed according to ISO 7027 (EN 27027, introduced in Europe since 1994) use light with wavelength > 800 nm to minimize interferences caused by the presence of dissolved light-absorbing substances (otherwise known as coloured dissolved organic matter or CDOM). ISO 7027 refers to its units as FNU (Formazine Nephelometric Units). Companies such as WETLabs are now marketing in-situ turbidimeters (such as those deployed by IMOS) that do not comply to method EPA 180.1 or to ISO 7027, as they measure backscatter at 700 nm. These instruments are calibrated with formazine standards, but can also be calibrated using scattering microbeads in SI units of m$^{-1}$.
Variability in the Measurement Of Turbidity

The units of NTU and FTU are subject to variations for different samples or detector types, due to sample properties such as the mean size or size distribution of suspended particles. Even when calibrated with the same standard Formazine solution, different turbidity meters give different NTU values, due to small differences in the optical design (Downing 2005). Hence as a standard unit, NTU data are not broadly comparable between different instruments, or even comparable from one deployment to another with the same instrument. Turbidity measurements for two different samples can only be compared if they have similar mean particle size and size distribution. Hence NTU measurements at best give only a relative indication of the amount of suspended matter in a water sample.

Hongve and Kesson (1998) present the results of an interlaboratory comparison where some participants used the ISO standard and some the EPA standard, to turbidities in the range 0-40 NTU/FNU and for colour up to 100 true colour units (TCU). They concluded that:
1) "Turbidimeters with spectral peak responses of the detection systems between 400 and 600 nm give most often lower readings than instruments that comply with ISO 7027 Section 3."
2) "Samples coloured by dissolved humic acid give lower readings than corresponding, less coloured ones, especially with instruments that operate in the wavelength range of visible light."
3) "For natural waters and suspensions other than formazine, the variation in light scattering properties of suspended particles had various effects in turbidimeters that do not comply with the international standard and the reductions in measured turbidity were often much larger than those caused by colour."

Barter and Deas (2003) compared five different portable cuvette-style nephelometric turbidimeters using both formazine standards and natural waters. The mean results on formazine samples showed reasonable agreement between the different meters up to the 400 NTU range (coefficient of variation (CV) of approximately 2 to 7%). However for the natural samples the sample type strongly influenced cross-comparability of the meters, with CV values ranging from 7 to 44%, indicating higher variation in readings from the same sample measured on different instruments.

These results were confirmed in a test conducted by The Alliance for Coastal Technologies (ACT) in the USA using a Wetlabs ECO-BB-SB turbidity probe, where the relationship of NTU to TSS and particulate organic carbon (POC) was found to be site-dependent. Moreover, this study also identified a strong linear relationship between Turbidity (NTU) and beam attenuation (m⁻¹) in a range of water types (coastal/lakes/rivers) (ACT 2007).

Alternative Calibration Approaches

Due to the relative nature and variability of turbidity measurements, a number of researchers have recommended that turbidity be replaced with alternative measurement quantities having more meaningful units. Zaneveld et al. (1979) observed that turbidity units are suitable for estimating particle concentration, but are inadequate for describing the optical properties of water. They recommended that a combination of transmission and scattering measurements would be more useful. Downing (2006) recommends that optical backscatter is more suitable than turbidity for estimating suspended solids concentrations. The relationship between backscatter signal and sediment concentration is almost linear for a large range of suspended sediment concentrations (Downing 2006; Sutherland et al. 2000).
Boss et al (2009) also found that backscatter measurements showed good correlation with TSS. The correlation of an optical measurement with TSS was found to be sensor-specific. In coastal waters, the differences were significantly larger and tide phase dependent. Boss et al (2009) therefore recommended that the use of turbidity standards for assessment of TSS should be stopped, and that efforts be focused on calibrating by correlating backscatter data with TSS. Furthermore, co-located measurements of backscattering and attenuation were found to improve TSS prediction and provide compositional information about the suspended particles; when the ratio of backscatter to attenuation is high, the bulk particulate matter is dominated by inorganic material while when the ratio is low, the matter is dominated by organic material.

Davies-Colley & Smith (2001) recommended abandoning turbidity monitoring in favour of a more reproducible parameter, beam attenuation. In their view, measurement of the optical attributes of suspended matter in many instances is more relevant than measurement of its mass concentration. Moreover, nephelometric turbidity, an index of light scattering by suspended particles, is only a relative measure of scattering (versus arbitrary standards) that has no intrinsic environmental relevance until further calibration to a 'proper' scientific quantity.

Due to the SI units involved, backscatter and beam attenuation are considered ‘proper’ scientific quantities. Backscattering occurs when a photon travelling within a water column strikes a suspended particle (with dimensions >10 times the wavelength of light) and is scattered within the backward hemisphere, between 90 – 180° from its original direction. Quantitatively, backscatter depends on the ratio of the cross-sectional area of the particle (m^2) to its volume (m^3). Hence backscatter is measured in S.I. units of m^2/m^3 = m^-1, the same units as beam attenuation (Davies-Colley and Smith 2001). Backscatter measurements therefore have physically meaningful units that are readily comparable from one sample to the next.

A separate document is currently being prepared on how IMOS scattering meters should be calibrated using this recommended approach.

Conclusion and Recommendations
In summary, turbidity measurements are highly variable between sample types and instruments, such that turbidity in NTU is only a relative measurement that cannot be easily compared with other measurements made by the same or other instruments. This makes NTU a deficient choice of standard unit for turbidity sensors within IMOS. There is evidence in the literature that backscatter measurements (with S.I. units of m^-1) show good correlation to environmentally relevant parameters such as TSS (Boss et al. 2009; Downing 2006; Sutherland et al. 2000). Often such parameters are the desired outcome of turbidity measurements, and they can be more reliably derived from data in SI units. Based on the above, NTU calibrations of IMOS backscatter and turbidity sensors are not recommended, and all future calibrations should be conducted in SI units. A detailed calibration protocol document is being prepared separately, and will be circulated to relevant IMOS data users when available.
References

ACT (2007). Performance Verification statement for the Wet Labs ECO-BB-SB Turbidity Probe (ACT VS04-07), Alliance for Coastal Technologies, Solomons, MD 20688, USA. URL: http://www.act-us.info/


