A NEW SENSOR FOR TURBIDITY AND SEDIMENTATION ANALYSES IN NATURAL WATERS

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Abstract: Two traditional turbidimeters are used to analyze natural waters. The EPA 180.1 sensor, a white-light nephelometer, covers a wide range of particle sizes but is influenced by water color and is difficult to miniaturize. The ISO 7027 sensor, an infrared nephelometer, is not influenced by water color but has poor sensitivity to larger particles. Both methods are defined only for turbidities up to 40 turbidity units even though field turbidities often exceed 5000 NTU.

A new turbidity sensor uses four incident colors to reduce water-color and particle-size biases. The new sensor detects light scatter at 0 degrees and 90 degrees off the incident beam to extend the dynamic range of the sensor and obtain an inherent correction for lens fouling.

The eight data (four colors, two paths) collected in each measurement cycle can correlate with sediment loads and characteristics when used in a multivariable regression model built with empirical sediment characteristics. The resulting "signature" is useful not only for calculating continuous sediment loads, but also in comparing sediments from other locations or conditions.

THE PROBLEMS WITH TURBIDITY MEASUREMENTS

What is turbidity? Turbidity is a qualitative term for the influence of entrained foreign matter on water's optical properties. Field turbidity measurements help determine light available for photosynthesis, aesthetics (303d listings), and sediment transport. The closest thing to a quantitative turbidity definition is that one nephelometric turbidity unit (NTU) is 1/4000 of a set recipe for formazin.

Turbidity has several conflicting definitions and measurement methods. Early definitions did not specifically address absorption (capture of visible, ultraviolet, or infrared light energy by water and entrained foreign matter), scattering (deflection by foreign matter of light energy from its normal path), or fluorescence (light absorbed and then re-emitted at a different wavelength).

More recently, ASTM standard D 1889-00 calls turbidity "an expression of optical properties of a [water] sample that cause light rays to be scattered and absorbed rather than transmitted in straight lines through a sample". A USGS work group adds "any suspended or dissolved particle that is capable of causing light to be scattered or absorbed should be expressed in a turbidity measurement". This definition recognizes that optical turbidity sensors are not particularly selective – they can't separate different types of influences on light transmission in water.

What are the problems of turbidity measurement?

- EPA Method 180.1 turbidity measurement requires the incident radiation of a tungsten lamp (white light) and a light path for incident light and scattered light not to exceed 10 cm. The 180.1 nephelometer covers a wide range of particle sizes, but is influenced by water color. The sensor's power requirements make it difficult to miniaturize, and so 180.1 is not often used for field measurements.

- ISO 7027 turbidity measurement requires an incident radiation of 860 nm (infrared light, IR) and a light path for incident light and scattered light not to exceed 1 cm. The ISO nephelometer is not influenced by water color, but has poor sensitivity to larger particles. Because ISO does not meet the regulatory definitions of 180.1, but can be accomplished with inexpensive, low-power LED's, ISO is used most often in field measurements.

- The ISO standard is defined only for the range of 0 – 40 NTU. Diluting samples into the 0 – 40 NTU range is expensive to apply to multiple samples in natural waters, and infeasible to apply when continuous turbidity data are desired.

- ISO 7027 sensors typically employ one light source and one light detector and so return only one datum per measurement cycle. This limitation of data, and the bias in that data (due to different sensitivities to different particles), make accurate estimates of other useful parameters (for instance total suspended solids) difficult to produce.

- Small variations in the different sensors from the different manufacturers, including linearity algorithms, can result in large measurement disagreements of up to 40% of reading or more, even when calibrated with the same solution.

- There are a dozen or more turbidity units (NTU, FTU, FTTU, RTU, etc.) that are similar but not equal. Each unit refers to a slightly different measurement technique, meaning those data are not directly comparable. A suggested reporting convention includes the turbidity-measurement method, light wavelength, detector orientation, and number of sources and detectors – quite a burden for large, water-quality databases.

- Formazin is difficult to prepare, has a short shelf life, and is a suspected carcinogen. Yet the calibration value of polymer beads is not defined analytically; it's referenced to a set formazin recipe as measured by a specific manufacturer's specific instrument model.

A NEW APPROACH TO TURBIDITY MEASUREMENT

The New Sensor in Theory: A new turbidity sensor adds three features to the traditional field turbidity-measurement technique (ISO 7027).

- First, the sensor uses the dual-beam, ratiometric measurement technique (Figure 1, showing four incident beams, four scattered beams, and four transmitted beams) often found in process-control turbidimeters. This method combines the benefits of transmitted light measurement and scattered-light measurement, providing a wider linear range, relative insensitivity to lens fouling, and better color rejection than the ISO technique.

- Second, the new sensor employs multiple wavelengths, covering IR and the visible range. The resulting data can be used to calculate an optical value which, though similar in concept to a traditional turbidity value, is less sensitive to (or biased by) water color and particle size, shape, and color. The sensor has the ability to mimic both the white-light (EPA) and IR (ISO) turbidimeters if desired.

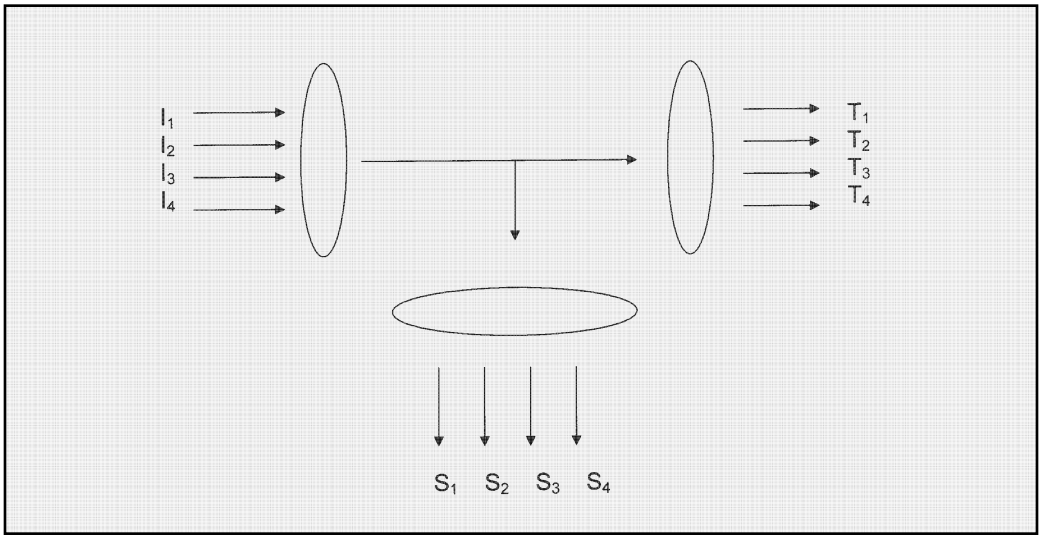

Figure 1 The New Sensor in Theory.

- Third, the new sensor has the rigorous construction and calibration methods that facilitate a new, well-defined optical index for water. Its materials, tolerances, etc. can be tightly specified so that Manufacturer A's sensor matches the performance of Manufacturer B's sensor when calibrated with the linearizing media (polymer beads) whose material, size, shape, color, etc. are specified unambiguously. This consistency produces the opportunity for a new, consistent optical index to replace the dozen or so measurement units in use today. The new measurement unit – call it the Environmental Optical Index - will be defined by linearity with linear dilutions of the absolute calibration solution.

- Fourth, the sensor produces a different combination of responses for different types of particles. These differences, carried in the eight data gathered per measurement cycle, can be used to characterize different combinations and concentrations of particles.

<u>The New Sensor in Practice:</u>

- The sensor uses sequentially-pulsed infrared, red, green, and blue light-emitting diodes (LED's) measured at 90 degrees and 0 degrees to produce eight data per measurement cycle to reducing particle-size bias while increasing accuracy and range. The configuration is shown below.

- The sensor is calibrated with white polymer beads with 1.0 µm mean size and 0.1 µm standard deviation, and linearized to any concentration or dilution of that calibration solution. This, along with specific construction specifications, ensures comparability of data taken with different individual sensors.

Figure 2 The New Sensor in Practice.

- The sensor uses all eight data per measurement cycle, combined in the expression shown in the figure above, to produce one turbidity reading. For convenience, a reading of 4000 environmental optical units is assigned the polymer-bead concentration corresponding to 4000 NTU.

- The sensor has an auxiliary function in which the eight data from each of several dilutions of a water sample are stored in memory, along with the sediment load (or other variable). A multivariable regression is used to create an algorithm for continuously estimating sediment loads (or other variable). The algorithm will be valid for dilutions of water containing the same type particles as did the calibration water, and may apply with various accuracies to waters with slightly different particle populations. Algorithms can be saved for different field conditions, for instance a certain stream after a rainfall event of a certain magnitude.

- The sediment "signature" resulting from the regression described above can also be used to compare sediments from different locations or conditions by comparing the correlation coefficients and other statistics available with multivariable regression models. For instance, clay suspensions may be explained primarily by a red light scattered at 90 degrees, secondarily by infrared light transmitted at 0 degrees, and not at all by either green signal – it can thereafter be inferred that other waters matching that "signature" may be similarly loaded with clay.

EXAMPLE DATA

Figure 3 shows the ratiometric measurements (90-degree response divided by 0-degree response) in Formazin solutions up to 2000 NTU. Note the differences in response slopes between the four light colors. The higher responses with the higher slopes are preferred for instrumentation as they represent larger electrical signals, but the other responses carry information, too. Also note the descending order of the light-color responses: blue, green, red, IR.

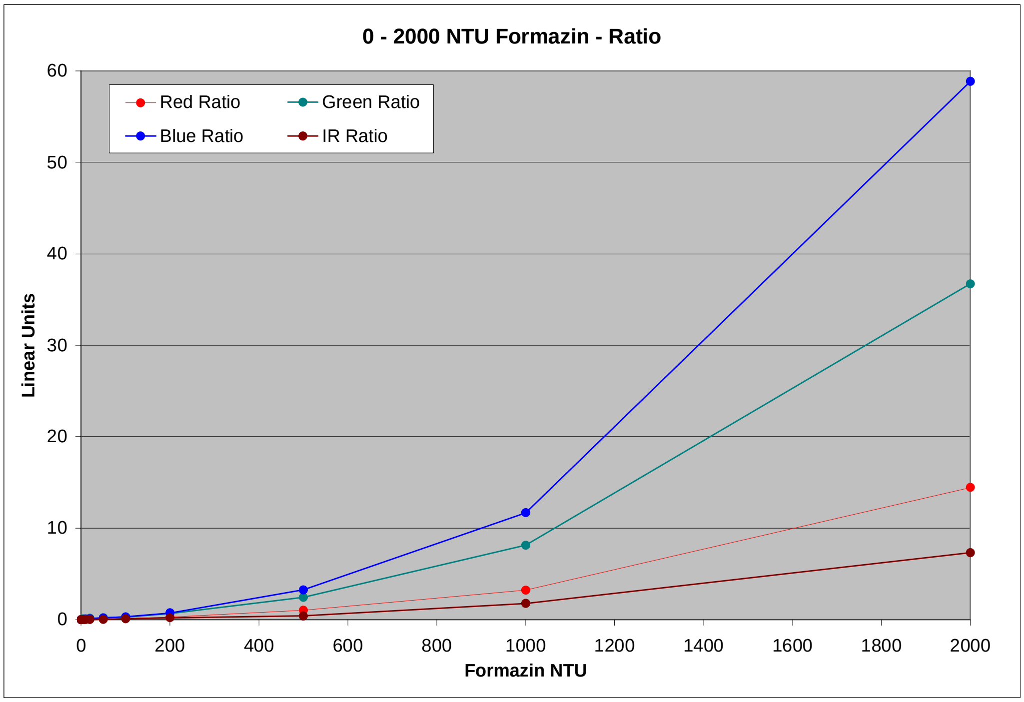

Figure 3 The New Sensor's Ratiometric Response to Formazin Dilutions.

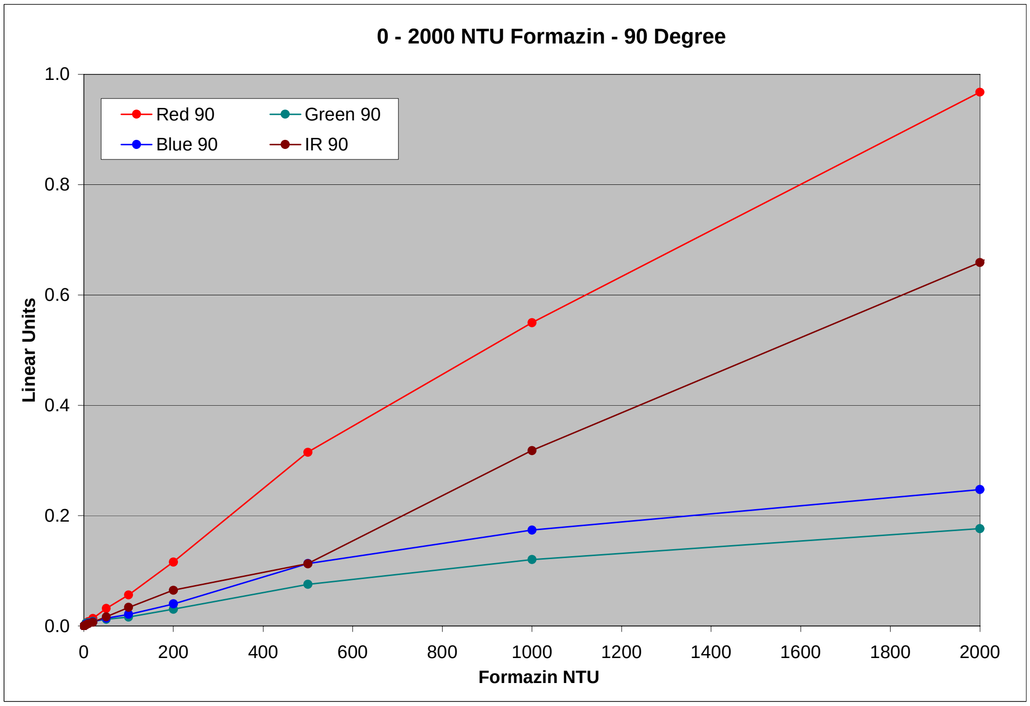

Figure 4 The New Sensor's 90-Degree Response to Formazin Dilutions.

Figure 4 shows the 90-degree (i.e., nephelometric response) of the sensor in Formazin solutions up to 2000 NTU. Again, note the differences in the response slopes of the four colors. But notice also that the descending order of the light-color responses has changed to red, IR, blue green from blue, green, red, IR. This is the differential behavior indicates the desired sensor operation: different responses from the different colors and light paths. These different responses carry information useful in discriminating between different types or sizes of particles.

Formazin is relatively uniform white color with somewhat variable particle size and shape. It does not color its carrier water. “Dirt” mixed with water, on the other hand, can have a wide range of particle characteristics, and may impart color to its carrier water. Figure 5 shows the new sensor’s responses in a mixture of brown, fine-particle garden soil and water. Unlike the more predictable Formazin, the responses of the different light colors are so different that they cross one another in the ratiometric mode – and appear in a different order. Figure 6 shows yet another behavior.

Does the new sensor carry any information not found in the traditional, 90-degree IR measurement? Figure 7 shows a section of a regression report (first-order, least-squares) using the IR 90 data from Figure 6. The adjusted R-squared value is 0.94 – not bad.

Figure 8 shows a multivariable regression (first-order, least-squares) using all four colors’ 90-degree responses and all four colors’ 0-degree responses. The adjusted R-squared value is 1.00, indicating a significantly better predictive power for the extra seven types of data provided by the new sensor.

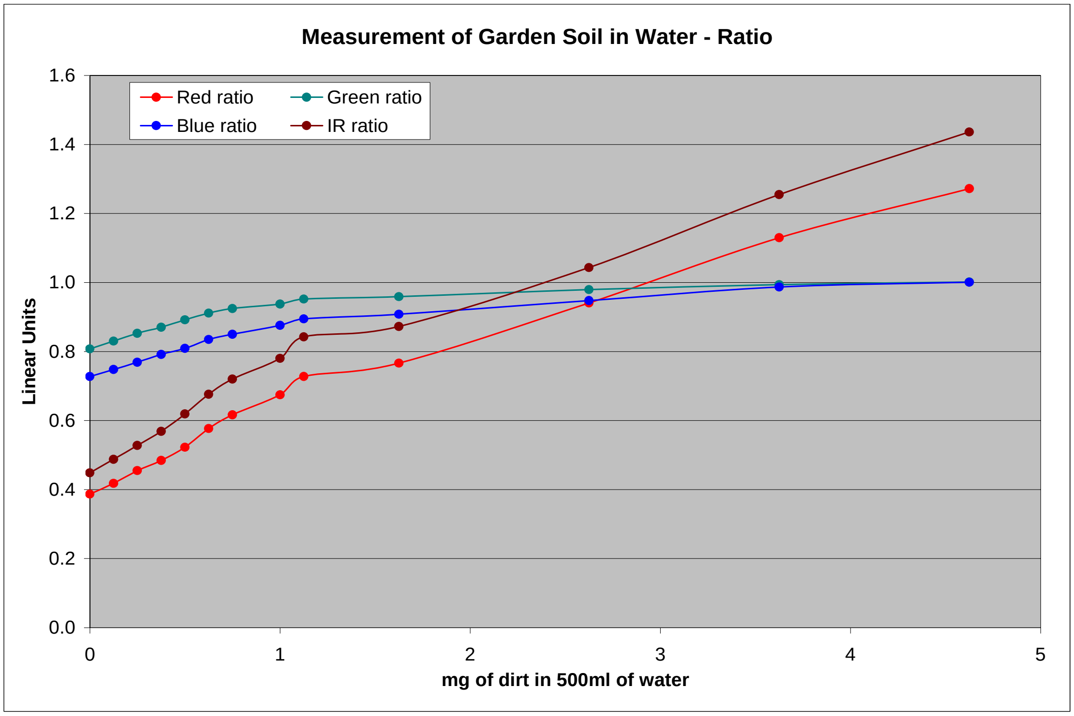

Figure 5 The New Sensor’s Ratiometric Response to Dirt Dilutions.

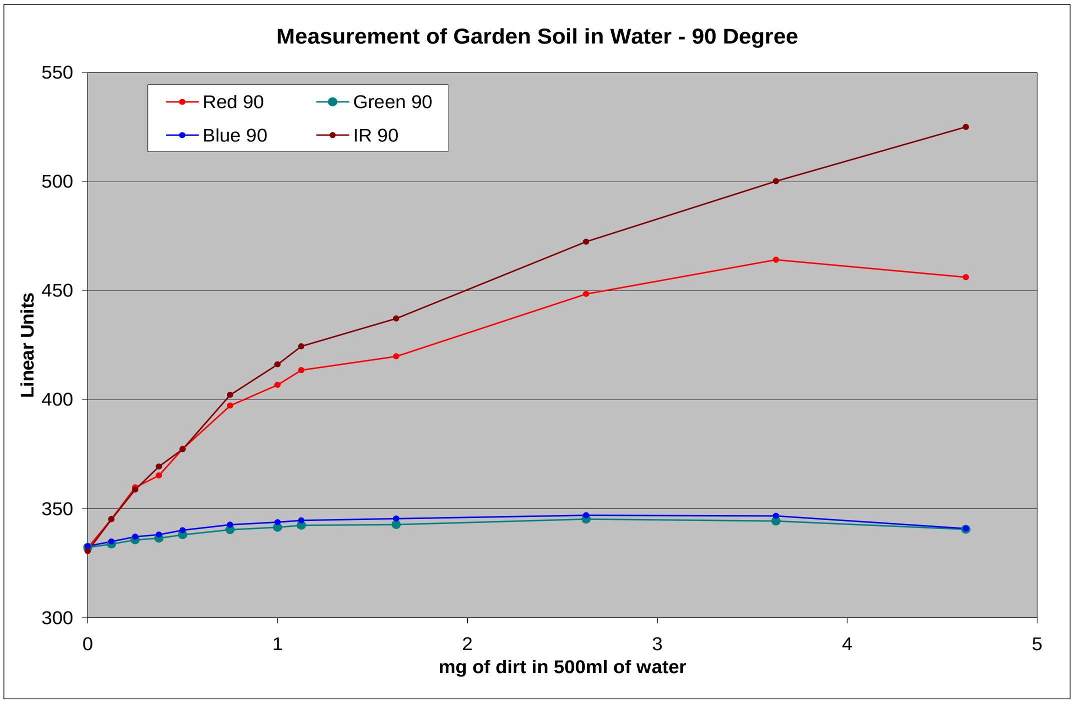

Figure 6 The New Sensor's 90-Degree Response to Dirt Dilutions.

Output for Soil mg

Regression Equation
Soil mg = - 8.15 + 0.02*IR 90

Summary Statistics

Criterion	Value
R^2	0.94
R^2 adj	0.94
R^2 predict	0.90
R^1	0.76
PRESS	2.37
s (est. err.)	0.36

ANOVA

	df	SS	MS	F	p-value
Regression	1	23.43	23.43	180.32	0.00
Residuals	11	1.43	0.13		
Total	12	24.86			

Coefficient Estimates

	Coefficients	Standard Error	t Stat	p-value	Lower 95%	Upper 95%	VIF
const	-8.153508	0.71	-11.43	0.00	-9.72	-6.58	
IR 90	0.022988	0.00	13.43	0.00	0.02	0.03	1.00

Figure 7 Regression Statistics for IR-90 Predictions of Soil Loading.

Notice that the regression outputs contain a listing of the coefficients due each light variable. Those coefficients provide a "fingerprint" unique to a particular empirical calibration curve.

Figure 9 shows the predictor curves for the IR-90 and Eight-Data predictors, along with a curve illustrating ideal behavior. The IR-90 predictor has an error of nearly 50% at 1 mg/l soil; the new sensor's predictor is nearly coincident with the ideal behavior.

Output for Soil mg

Regression Equation

Soil mg = 66.21 + 0.06*RED 90 - 0.01*RED 0 - 0.03*GREEN 90 - 0.00*GREEN 0 - 0.24*BLUE 90 - 0.02*BLUE 0 + + 0.00*IR 90 + 0.02*IR 0

Summary Statistics

Criterion	Value
R^2	1.00
R^2 adj	1.00
R^2 predict	0.98
R^1	0.97
PRESS	0.47
s (est. err.)	0.08

ANOVA

	df	SS	MS	F	p-value
Regression	8	24.83	3.10	480.49	0.00
Residuals	4	0.03	0.01		
Total	12	24.86			

Coefficient Estimates

	Coefficients	Standard Error	t Stat	p-value	Lower 95%	Upper 95%	VIF
const	66.21	51.09	1.30	0.26	-75.62	208.05	
RED 90	0.06	0.04	1.71	0.16	-0.04	0.17	5122.77
RED 0	-0.01	0.01	-0.77	0.48	-0.03	0.01	2267.25
GREEN 90	-0.03	0.19	-0.15	0.89	-0.54	0.49	1005.00
GREEN 0	0.00	0.03	-0.15	0.89	-0.08	0.07	695.63
BLUE 90	-0.24	0.22	-1.09	0.34	-0.84	0.36	1757.50
BLUE 0	-0.02	0.03	-0.62	0.57	-0.10	0.06	2123.95
IR 90	0.00	0.02	0.12	0.91	-0.06	0.06	3165.31
IR 0	0.02	0.01	1.78	0.15	-0.01	0.05	2830.14

Figure 8 Regression Statistics for Eight-Data Predictions of Soil Loading.

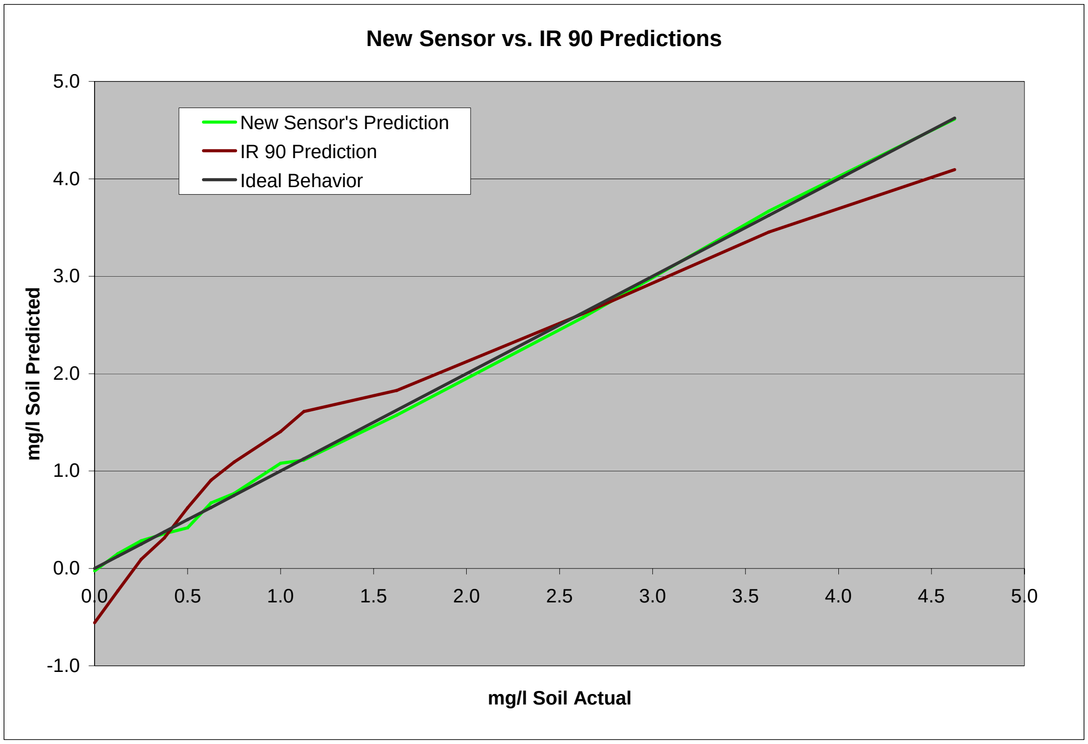

Figure 9 Differences in Predictive Models.