Observations on Secchi Depth Measurement Variability

(A report to the Wisconsin Department of Natural Resources)

Contents

Part 1 Summary
Secchi Depth Using Artificial Light

To investigate using nighttime Secchi depth measurements as a reference for quantifying daytime measurement variability, artificial light sources were evaluated in a clear lake and a turbid lake. LED devices were found to be the most suitable light source because they have sufficient intensity, excellent intensity consistency, and a long battery life. A triangular arrangement of 3 Streamlight E-Spot™ LED lamps provided the best overall intensity and beam diameter. Using this arrangement in a preliminary study, the night readings were within 8% of the daylight readings in both lakes when compared to daylight readings corrected to zenith solar altitude. The clear lake showed significantly less clarity variability at night than during the day while the turbid lake showed about the same variability at night as during the day. Further study would be needed to establish nighttime measurements as a credible reference to estimate daytime measurement variability.

Part II Summary
Current Tools to Estimate Secchi Depth Measurement Variability
(Due to Solar Altitude, Waves & Ripple, and Reflection Effects)

Data collected over the period 2006-2008 on a small lake in Wisconsin produced an example for estimating the Secchi depth measurement variability due to solar altitude variation, waves and ripple, and reflection. Estimates were based on (1) a model which corrects for the range of solar altitude experienced in the State and (2) the use of a viewscope to reduce the effect of wind and reflection. This estimate is believed to be conservative because the lake is protected from wind and because all sources of measurement variability were not included. This example estimated the average range for measurement variability to be +/- 12% while reaching +/- 20% under windy conditions.

Recommendations for Part I and Part II

1. Start including data collected with a viewscope for a representative sample of lakes in Wisconsin. Use this data in conjunction with solar altitude corrections to improve estimates of the degree of Secchi depth measurement variability in the State.
2. Explore seeking a volunteer team to perform further day/night Secchi measurements on 3 lakes whose clarity spans from low to medium to high. Use the data collected to build a broader knowledge of how nighttime clarity compares to daytime clarity.
3. Inform Wisconsin Citizen Lake Monitoring Network members that the Secchi depth measurement will vary for reasons other than the clarity of the water they are measuring, especially during windy periods. If local lake managers are starting to collect Secchi depth trending data for their lake, make them aware of the increased accuracy possible from using a viewscope.

Background for this Report

The Secchi depth measurement is likely the most-used method to monitor clarity of waterbodies around the world. This popularity results from the simplicity of implementation and the easily understood general meaning of the measurement. However, when using the measurement for building understanding of how a waterbody works or for managing a waterbody, uncertainty of the accuracy and precision of the measurement often relegates it to a “ball-parking” category.

Uncertainty of the accuracy and precision has been reviewed in several journal articles (Preisendorfer, 1986), (Tyler, 1968), (Davies-Colley & Smith, 2001). Factors other than the inherent properties of the water column being measured are known to contribute to the Secchi depth value. Hence the Secchi depth value is often called an apparent optical property of the water under study. For this investigation, the factors that contribute to measurement variability were simply thought of as external factors. These external factors are those that influence the measured value but are not properties of the water column itself. Examples of external factors are solar altitude, waves and ripple, surface reflection, clouds and haze, shadow of the watercraft, disk color and reflectivity, and observer differences.

Measurement variability, for the purposes of this report, is considered a component of the total measurement variation which adds uncertainty to the magnitude of the true measurement. All scientific disciplines require knowledge of measurement variability to allow meaningful interpretation of the measured data. For the Secchi depth measurement, the measurement variability information available is typically insufficient to determine statistical confidence in the conclusions drawn from the data (Smith & Hoover, 1999; Smith, 2000).

The 2 lakes measured in this report are located in northeastern Polk County. The Pipe Lakes consist of 296-acre Pipe Lake and 66-acre North Pipe Lake in the Upper Apple River Watershed in Polk County, Wisconsin. North Pipe Lake has an outlet which flows to Pipe Lake. Pipe Lake’s watershed is 2070 acres which includes North Pipe Lake’s watershed of 1106 acres. Both Lakes have most of their shoreline developed with private cabins and homes. Both lakes’ watersheds remain largely forested with a smaller portion in agriculture. Pipe Lake is designated an Outstanding Water Resource by the State of Wisconsin. Its May-September Secchi clarity depth averages 16.3 feet. North Pipe Lake has an average May-September Secchi clarity of 7.2 feet. It is mildly eutrophic and also becomes visibly stained from tannins in the watershed during high runoff periods.

Part 1
Secchi Depth Using Artificial Light

Introduction

To seek improved understanding of the overall measurement variability of the Secchi depth measurement, the Wisconsin DNR, through its Citizens Monitoring Partnership Program, funded a 2010-2011 feasibility investigation of utilization of artificial illumination as a quasi-reference. The concept behind this investigation was to measure Secchi depths during the day under a variety of waterbody, seasonal, weather, and protocol conditions. These measurements would be preceded or followed by measurements utilizing controlled artificial illumination during the night. If the measurements at night employ a viewscope (Figure 1), most of the measurement variability sources that occur in daylight hours should be eliminated or greatly reduced. With the assumption that the inherent properties of the water column would be the same, or nearly the same, during the day as at night (preceding or following the day), the differences in variability between the daylight and night measurements should be a measure of the measurement variability encountered using a standardized daylight protocol.

This investigation concept also assumes the artificial light source sufficiently simulates daylight and, therefore, does not introduce misleading effects.

This study was planned to consist of 2 phases. Phase 1 was to define an artificial source that works at night as a reasonable facsimile of daylight Secchi measurements. Phase 2 would be to estimate measurement variability for the day protocol through a series of day/night measurements if Phase 1 could be satisfactorily completed. This Part 1 report is a discussion of Phase 1 work and preliminary Phase 2 work completed during the 2010 summer on the 2 lakes in Northwest Wisconsin. The Phase 1 work evaluated light sources and their deployment. The preliminary Phase 2 work compared measurements throughout a day on each lake with their respective night readings.

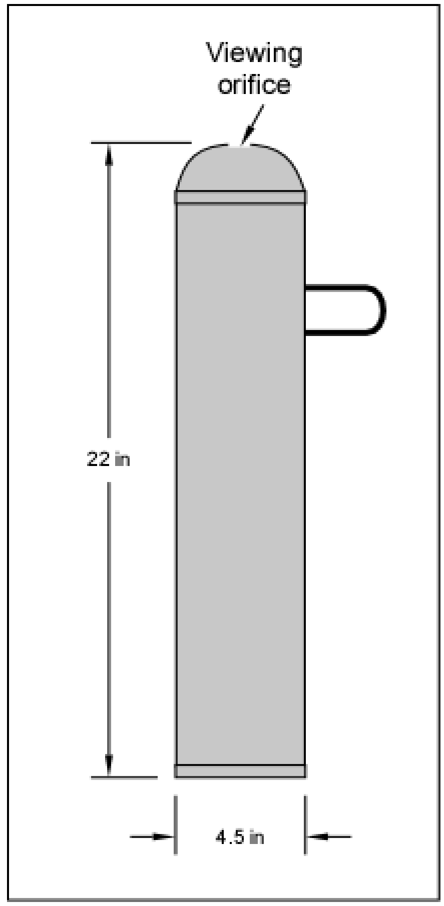

Figure 1 - viewscope

Procedures

Where applicable, Wisconsin's Secchi depth measurement protocol (Betz, Howard, Wickman, & Herman, 2005) was used for the measurements in this study:

> The general measurement protocol in Wisconsin is to take readings with a 20-cm black and white quadrant disk from the shady side of an anchored boat on a clear and calm day between 10 a.m. and 4 p.m. central daylight time. Slowly lowering the disk until it disappears gives one depth point. Slowly raising the disk until it reappears gives a second depth point. The midpoint between depth of disappearance and reappearance is the Secchi depth result.

Procedures also used but not defined by the Wisconsin protocol:

1. All Secchi depth data points consisted of averaging 3 consecutive trials.
2. All daylight measurements included trials with and without a viewscope on both the sunny and shady side of the watercraft. The viewscope was closed on the bottom with a glass plate.
3. Night measurements were with a viewscope positioned about a foot from the light source center. Only a viewscope was used at night because the goal was to be as precise as possible at night.
4. The light source platform (Figure 2) was leveled on site once all objects in watercraft were positioned for measurement operations.

Equipment

The measurements in this study were from a 16-ft fishing boat in Pipe Lake and from a 22-ft pontoon in North Pipe Lake. All measurements were at the "Deep Hole" location in the lakes. An Extech HDS400 light meter provided all Illuminance (lux) measurements. All Secchi depth measurements were with a new Secchi disk and line assembly provided by the University of Wisconsin Extension – Lakes. Artificial light source equipment is described in the following section.

Figure 2 Lanterns mounted on platform with adjustable tilt.

Light Source Evaluation

Measurement Technique Development

Initial attempts to measure Secchi depths at night were with a 630 lumen LED flashlight attached to the side of a viewscope. The viewscope was tilted slightly to both view the disk in the water and to aim the beam at the disk. In the clearer lake (Pipe) with Secchi depths from 25-30 feet, keeping the beam centered on the disk was cumbersome as the disk was lowered to the point of disappearance and then raised to reappearance. In daylight, the sun illuminates all points in a horizontal plane at the Secchi depth equally. When the disk disappears in daylight, it disappears only because the eye can no longer detect the disk. With an artificial beam, the disk could also disappear (and fail to reappear) simply because it has drifted out of the beam's path.

To minimize this problem of being unsure if the disk remains in the beam's path, the following 4 modifications were devised:

1. Three sources were arranged in a triangle on a platform (Figure 2) to increase the effective beam diameter.
2. The disk line was guided through a hole in the platform at the center of the triangle arrangement.
3. The platform supporting the triangle arrangement was made capable of adjusting its tilt to level the platform on location. This allowed the disk to stay centered in the beam zone when lowered.
4. Retro-reflective tape was applied to the bottom of the disk (Figure 3) so that a 1-inch strip extended outside the disk edge facing upward. In Secchi depths greater than about 10 feet, this tape remained visible even after the disk disappeared. With the tape still visible, assurance that the disk was still in the beam was possible. In addition the tape helped to know where to look for reappearance of the disk, improving reliability of the nighttime measurement. This tape was not any more visible than the disk itself in the more turbid water sometimes encountered in North Pipe Lake. In this latter case, the distance from the source to the disk was sufficiently small so that keeping the beam on the disk was not as cumbersome as with the larger distances involved in clearer water.

Light Source Selection

The illuminance (intensity) of the sun at the earth's surface varies from about 10,000 to 120,000 lux. White light sources in this intensity range are available with tungsten, tungsten halogen, light emiting diode (LED), and xenon light types. Xenon sources tend to be more expensive than the other options so they were not evaluated in this study. The sources investigated produced intensities in the above range at about 4 inches from their face. Because the sun's rays are essentially parallel, its illuminance does not vary over Secchi depth distances (in air). A reasonably priced artificial source will however vary significantly in illuminance over the distances involved in an air medium. The effect of this fundamental difference between the solar source and artificial sources on simulating Secchi readings is not clearly understood.

Figure 3 top - disk with reflective tape bottom – disk lowered in the water while illuminated with a 3-lamp source and viewed by viewscope.

Battery life and constant illumination intensity are important to a night Secchi illumination source. As shown in Figure 4, 5 lamps that could potentially qualify for use at night were tested for intensity consistency. Only 2 of the lamps qualified assuming at least an hour of constant intensity is needed. LED lamps, because of their low power requirements can be designed to give constant intensity output. Tungsten lamps powered by batteries tend to lose intensity too rapidly if operated with lightweight batteries.

As mentioned earlier, a large diameter beam is desirable to prevent the beam from moving off the disk. Figure 5 plots the beam intensity in a direction across the lamp face. The Streamlight E-Spot lamps (500 lumens each) arranged in a triangle produced the best combination of a wide and intense beam. Figure 6 shows 3D plots at 2 distances from the lamp face of the spacial intensity distribution of the 6-inch-apart arrangement of E-Spot lamps. Figure 7 is a relative intensity versus wavelength plot for the E-Spot lamp. Except for the peak at 450 nm, this plot approximates daylight.

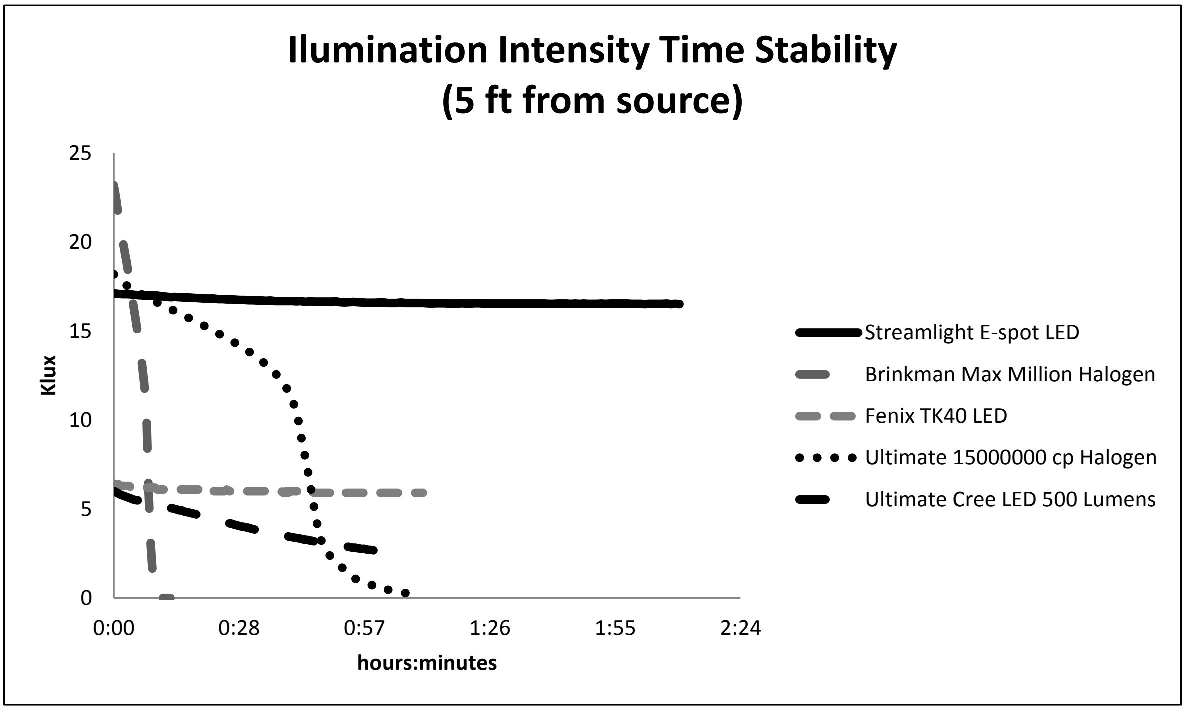

Figure 4

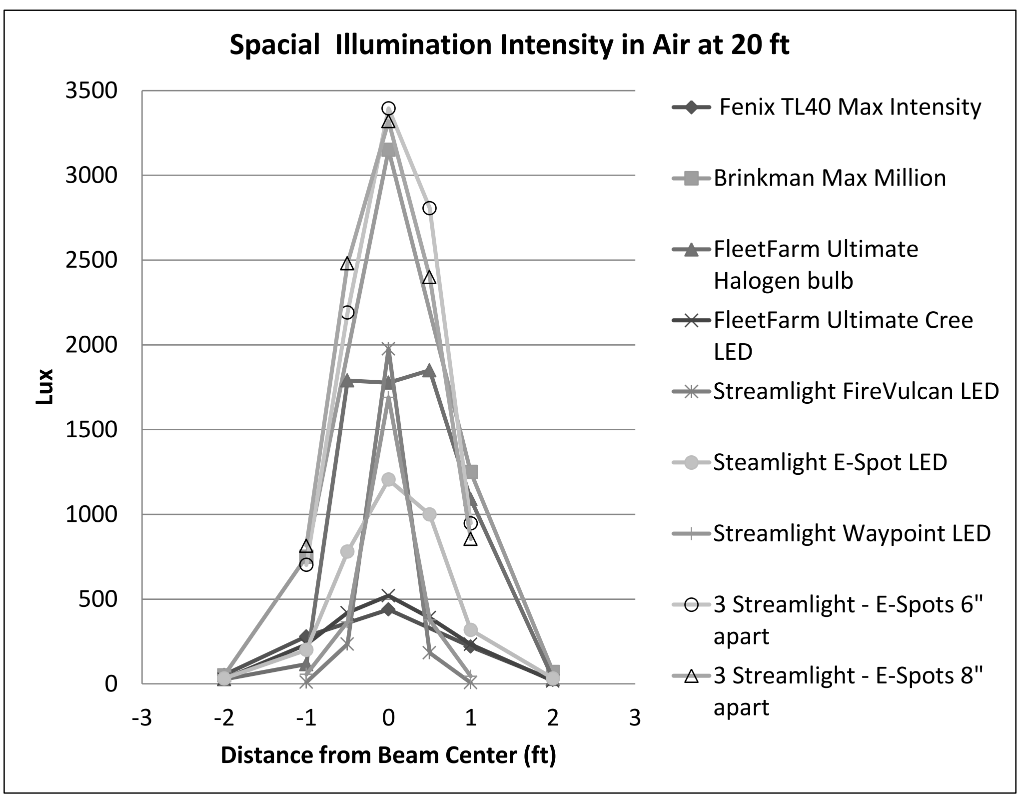

Figure 5

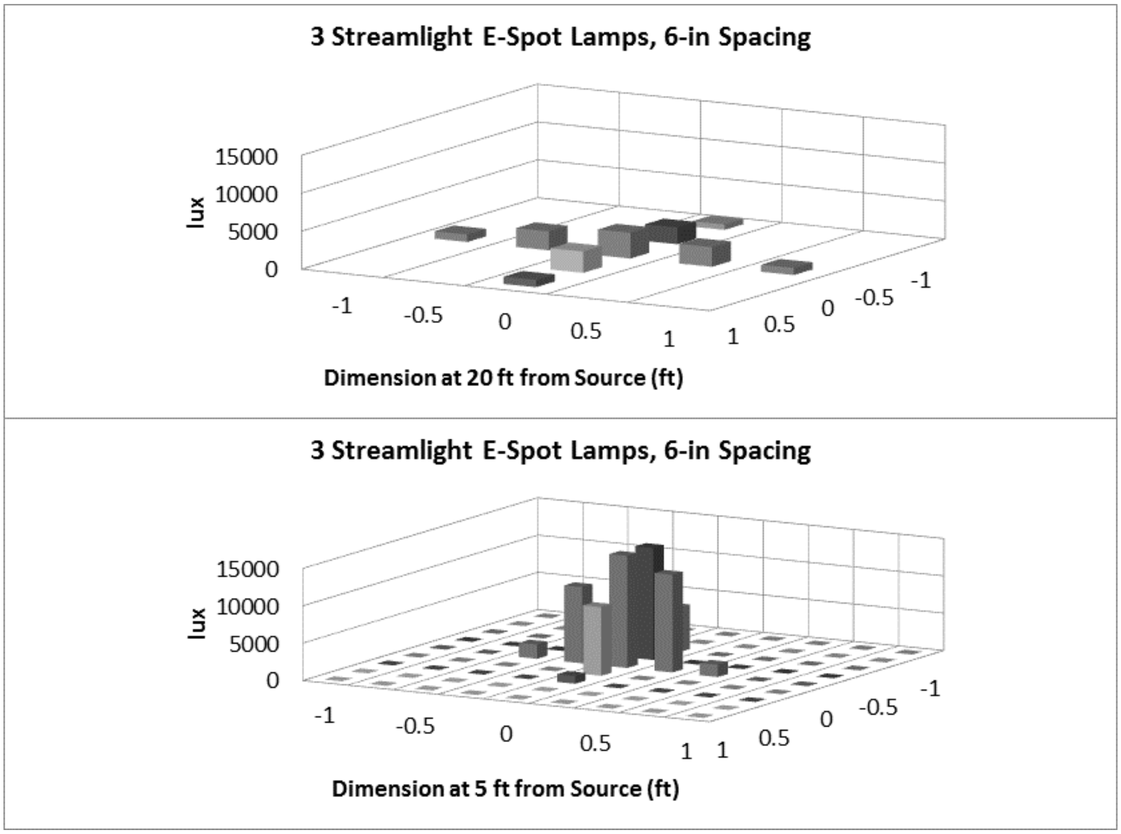

Figure 6

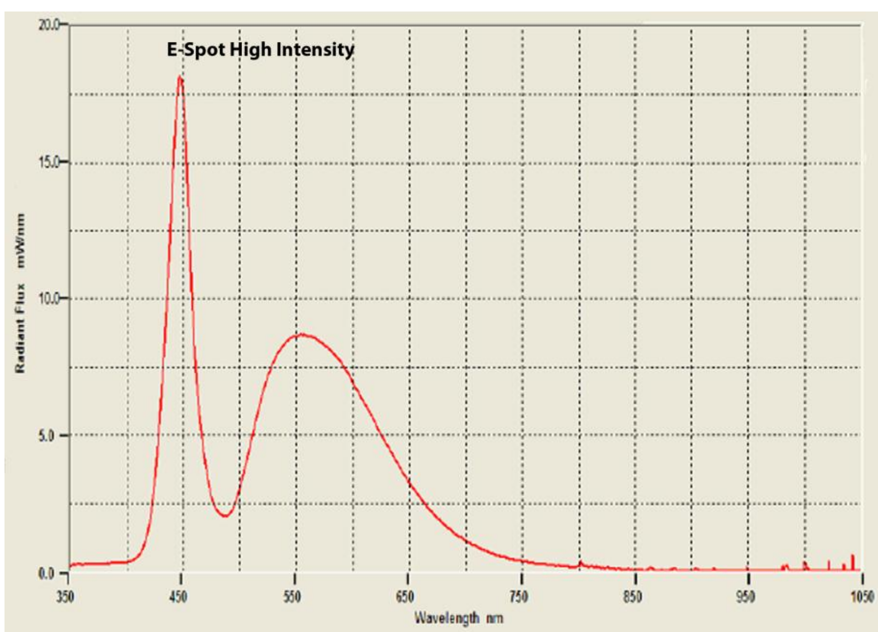

Figure 7 (Source – Streamlight Inc.)

Most lamp systems evaluated are listed in Figure 8 with their % difference between nighttime and daytime Secchi values. Figure 8 gives the % difference relative to daylight values with a viewscope on the sunny side. The daylight Secchi values in North Pipe Lake ranged from 4 feet to 11 feet while the range in Pipe Lake was from 16 to 25 feet. This figure seems to show

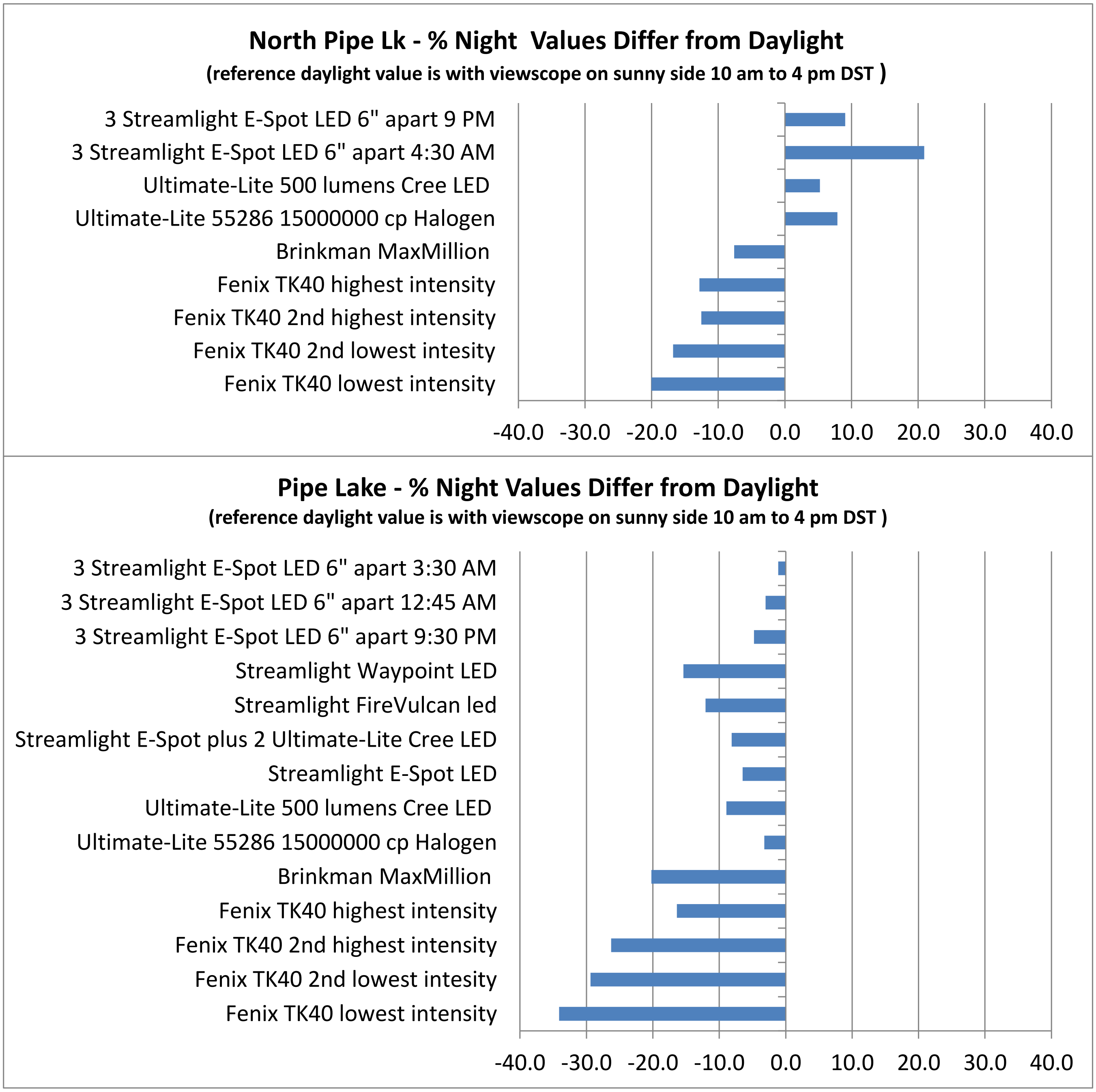

Figure 8

2 tendencies. One is that, within some unknown limit, increasing the intensity increases the Secchi value. The other is that the % difference is more negative on Pipe Lake (clearer) than on North Pipe Lake (less clear).

Preliminary Day/Night Study

With a night measurement system devised (Figure 9), a series measurements were made on both lakes to make a preliminary comparison between daylight and night measurements. On Pipe Lake, the study was from 12 pm on August 6th, 2010 to 1 pm on August 7th. The study on North Pipe Lake was from 4 am on August 22nd to 9:30 pm on August 22nd. Figure 10 and Figure 11 show the time series of the measured data – all points are 3-trial averages. Note that late night Secchi depths are larger than early night values in both lakes. But also note that daylight readings on Pipe Lake may have drifted higher from the 1st day to the 2nd day, possibly a continuation of the drift occurring overnight. The wind during these studies varied from relatively calm to breezy. Wave height never exceeded 1.5 inches during the day or 0.25 inches at night. During the day, full sun existed most of the time, but periods of partly cloudy to cloudy did occur for short periods. Heavy water skiing traffic occurred during the North Pipe daylight readings. The data collected is summarized in Table 1 below.

Figure 9

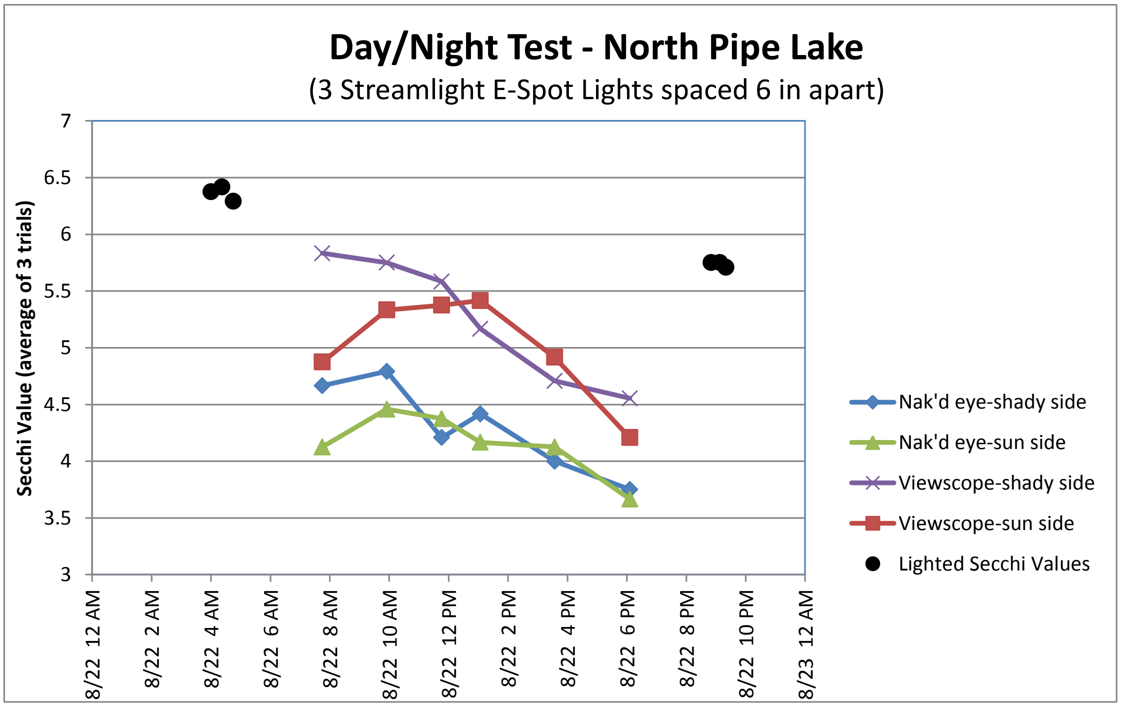

Figure 10

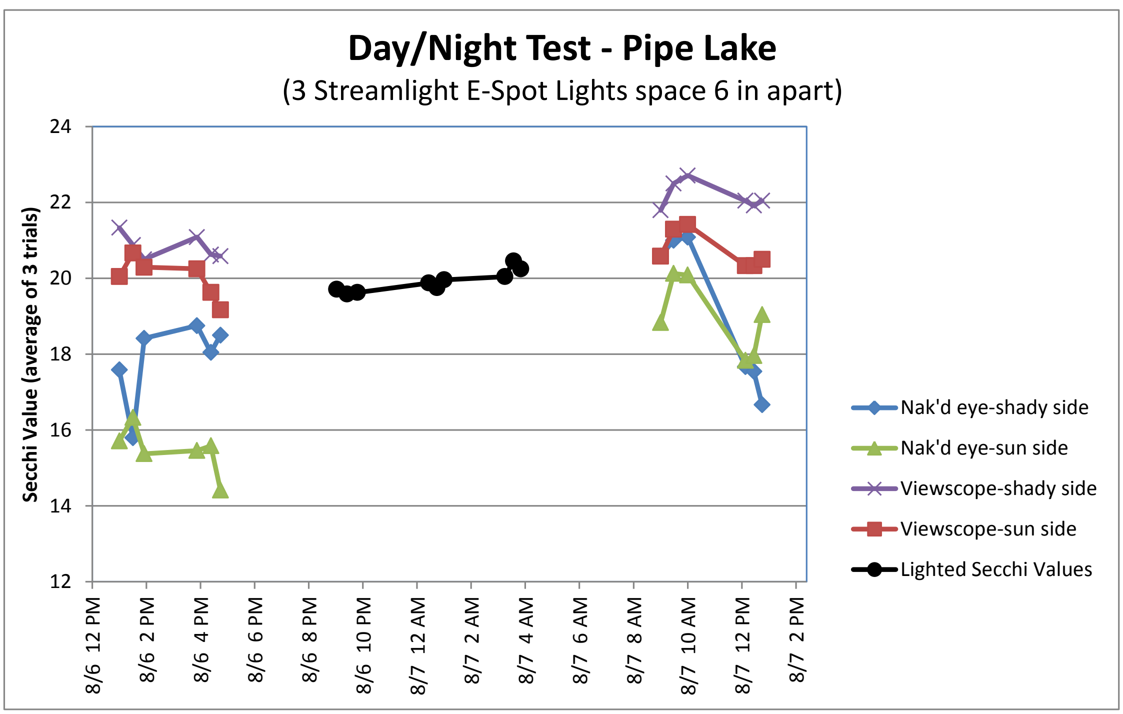

Figure 11

Table 1

Summary of Preliminary Day/Night Study

	10 am to 4 pm					9 pm to 4 am
	NeSd*	NeSn*	VsSd*	VsSn*	VsSn* Corrected to zenith	3 E-Spot*
	Number of 3-trial samples					
North Pipe	4	4	4	4	4	6
Pipe	8	8	8	8	8	9
	Avg Secchi depth (ft) for day or night					
North Pipe	4.4	4.3	5.3	5.3	5.7	6.0
Pipe	17.9	17.2	21.6	20.5	21.6	19.9
	Pooled std deviation (ft) within 3 trial sets for day or night					
North Pipe	0.09	0.14	0.10	0.14		0.10
Pipe	0.67	0.60	0.22	0.12		0.23
	Std deviation (ft) within day or night					
North Pipe	0.34	0.16	0.47	0.23		0.35
Pipe	1.57	1.77	0.73	0.42		0.29
	Coeff of variation (ft) within day or night					
North Pipe	0.08	0.04	0.09	0.04		0.06
Pipe	0.09	0.10	0.03	0.02		0.01

*NeSd - naked eye, shady side
*NeSn - naked eye, sunny side
*VsSd - viewscope, shady side
*VsSn viewscope, sunny side
*3 Streamlight E-Spot™ – lamps spaced 6-in apart

This table shows that variability decreased significantly in the clearer water of Pipe Lake when a viewscope was used whether during the day or at night. In the more turbid water of North Pipe Lake, variability is similar whether or not a viewscope was employed or whether measured during the day or at night. These data seem to imply that the measurement variability during the day on the clearer lake was large relative to measurement variability at night. But for the turbid lake, the measurement variability difference between day and night readings was near negligible.

Table 1 also shows good agreement between the magnitude of average daylight and average nighttime readings. The most exact comparison should be when comparing the nighttime readings corrected to zenith to the daytime viewscope readings on the sunny side. Under these conditions, the clear and turbid lake nighttime readings were 8% lower and 5% higher than the daytime readings respectively.

Discussion of Results

This evaluation of light sources demonstrates that commercially available battery operated artificial light sources produce Secchi depth measurements at night close to those obtained during the day. Through incorporation of special procedures and positioning methods, these lamps can simulate the basic characteristics of daylight measurements in the 4-ft to 25-ft Secchi depth range. However, this study also revealed several issues that should be resolved before a full Phase 2 study is initiated. These issues are conveyed below by answering a series of questions.

1. Do the 3 Streamlight E-Spot LED lamps mounted as described above adequately simulate daylight illumination for estimating Secchi depth measurement variability? Two unresolved concerns are:
    a. The inability of the commercially available battery operated lamps to produce rays nearly as parallel as the sun's rays could indicate an inability to adequately simulate the sun. Because the true effect of this difference on simulating Secchi depth measurements is largely an unknown, the difference could reduce the credibility of using nighttime measurements to represent daylight Secchi readings.
    b. Another potential argument against using artificial light is that the diffuse background light may be sufficiently different with artificial light to allow questioning of the simulation accuracy (Kirk, 1984).
2. How would a Phase 2 study need to be designed?

    Because some variation (drift) was found at night in the preliminary study, this phenomenon may add complexity to a Phase 2 investigation. For example, a method to subtract out that variability may be needed.

    To estimate the measurement variability, maybe 5-10 different lakes would need to be measured during the day and night over a May-September period. Volunteers could do this work, but the expectations would be more involved than that for the standard protocol. Several sets of lamp mounting equipment would need to be built.
3. Does enough monetary and volunteer support exist to complete a Phase 2 study?

    The largest difficulty in completing a Phase 2 study may be obtaining sufficient volunteers and professional participation to make the study complete enough to be credible.

This study has shown that artificial light has the potential to accurately and precisely measure in-situ water column transparency. Could the artificial light source system be useful for something other than studying Secchi depth measurement variability?

Conclusions

1. Measurement of Secchi depth at night with artificial light with precision exceeding that during the day was demonstrated.
2. To credibly estimate daytime measurement variability from night measurements will require further feasibility study and support of those institutions that rely on Secchi depth measurements.

3. The following unknowns need clarification before further evaluation of using artificial light at night to estimate measurement variability is undertaken:
    a. Do differences in the light distribution in the measured water column at night versus during the day confound the measurement variability estimate?
    b. What is the pattern of transparency variation at night among representative lakes?
    c. What is the practical effect of beam intensity on the measured Secchi value? How much does the falloff of artificial beam intensity with distance matter to measuring Secchi depth with artificial light?

Part II
Current Tools to Estimate Secchi Depth Measurement Variability
(Due to Solar Altitude, Waves & Ripple, and Reflection Variability Effects)

Tool Description

If the scope of a thorough investigation of using artificial light to estimate Secchi depth measurement variability should prevent a Phase 2 study, what is the next best option for producing insight on Secchi depth measurement variability? This may be to estimate the combined components of measurement variability caused by solar altitude changes, optical distortions from waves and ripple, and visual interference from specular reflection from the water. These estimates can be generated by utilizing a solar altitude model and a viewscope. The model (Verschuur, 1997) can remove the effect of solar altitude variation while the viewscope removes the effect of waves and ripple and surface reflection (Smith & Hoover, 1999).

Removing the solar altitude effect was first demonstrated in eutrophic waters (Verschuur, 1997). This model has since been demonstrated to apply also to very clear waters (Kleppe & Girdner, 2008). This model shows the relationship, in a clear sky, between a measured Secchi value at a solar altitude A and the expected Secchi value if the measurement were made at a different altitude.

$$Z = \frac{S(1+F)}{2F}$$

Where

$$F = \cos\left(\sin^{-1}\left(\frac{\cos A}{1.33}\right)\right)$$

A = solar altitude

S = measured Secchi depth

Z = measured Secchi adjusted to Zenith

The effect of waves and ripple as well as surface reflection can largely be eliminated by use of a viewscope (Craycroft, 2000), (Schloss & Craycroft, 2005), (Steel & Neuhausser, 2002) (Smith, 2000). A viewscope removes the obscuring of the disk that waves and ripple can cause. The viewscope also prevents the blinding effect of reflection off the water surface to the eye.

Data Collection

Secchi data was collected from North Pipe Lake in 2006-2008 from May through September on both sides of the watercraft with and without a viewscope. In 2006, these measurements were replicated 6 times and averaged. In 2007 and 2008, 3 replications were taken. This produced 36 measurement sets over the 3-year period. These measurements were adjusted to convey the effect of altitude locally and across the State of Wisconsin. In addition, viewscope measurements on the sunny side were used to show the effect of wind and reflection on naked eye measurements. Using sunny side measurements with the viewscope eliminated the variable effect of the shadow of the watercraft when using data from the shady side. All measurements were taken between 10 am and 4 pm CST. Most of the measurements were taken in full sun. In a few cases, clouds or haze were present, but a strong shadow was produced. Wave height was typically less than 2 inches with extremes of 4 inches. Because North Pipe Lake is small and surrounded by heavily wooded banks, the tendency of wind to decrease naked eye readings would be expected to be smaller than in larger and less protected lakes. In addition, a clearer lake may be more susceptible to measurement variability to wind and reflection effects (Schloss & Craycroft, 2005).

Results

Figure 12 shows how each of the 36 measurements can vary due solar altitude changes and different conditions of wind and surface glare, even though they are measures of the same water clarity. The lowest readings would be expected if all 36 sets of readings were taken following the protocol to measure on the shady side of the watercraft without a viewscope (naked eye) but at the solar altitude occurring in late September at 10 am (when the solar altitude is the lowest for the season). The highest readings would be expected if all of the readings were taken on June 21 when the solar altitude is the highest and with a viewscope (to eliminate the effect of wind and surface glare). The difference between these lowest and highest readings for each of the 36 measurement sets provides insight into the nature of measurement variability.

Table 2 summarizes the Figure 12 plots. Included is the additional solar altitude effect due to north versus south locations, a relatively small factor. Of course, if comparing a northern Wisconsin lake to a Florida lake, a larger location effect due to solar altitude would occur. Using this 2006-2008 example data, Secchi measurements would be expected to vary within the State +/- 12% from the median of a series of measurements of the same water column on average with some samples reaching +/- 20%. Stated another way, for a lake whose true clarity reading is 10 feet, the typical reading (an average of 3 readings) would be expected to range from 8.8 feet to 11.2 feet, and some readings will be as low as 8 feet and as high as 12 feet. The altitude effect range due to measuring at various times during the day and the north and south extreme locations of the State are a fixed +/- 7.3% from the median.

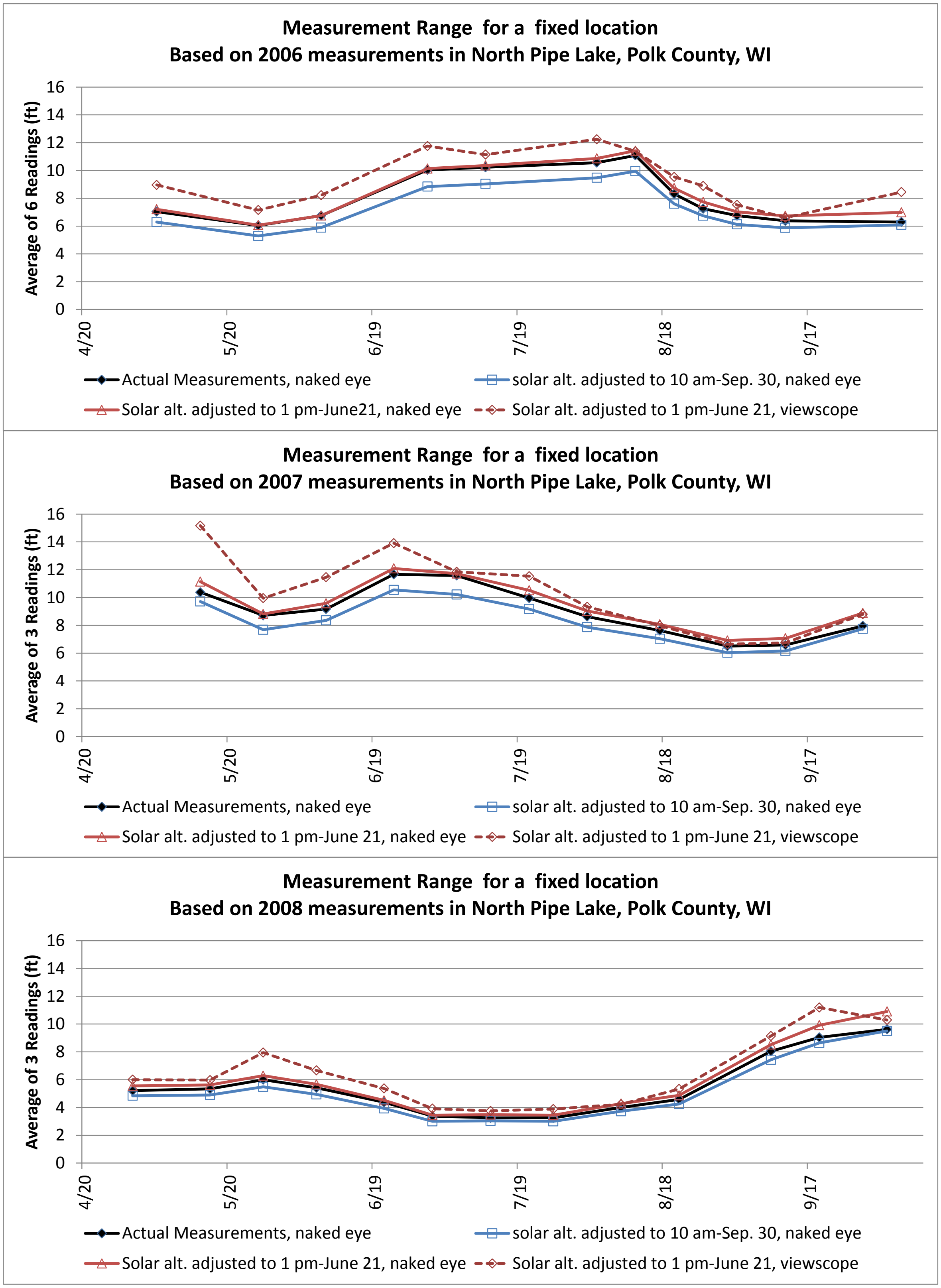

Figure 12 Measurements include 2 extremes: (1) solar altitude adjusted to June 21 at 1 pm with viewscope on the sunny side and (2) solar altitude adjusted to September 30 at 10 am with naked eye on the shady side.

Table 2

May-September Secchi Depth Measurement Variability Example Summary*				
	Statewide		Local	
	Altitude only	Alt, Wind & Reflection	Altitude only	Alt, Wind & Reflection
Average deviation	+/- 7.3%	+/- 12.2%	+/- 6.9%	+/- 11.5%
Average annual maximum deviation	+/- 7.3%	+/- 19.7%	+/- 6.9%	+/- 19.3%
Average annual minimum deviation	+/- 7.3%	+/- 7.3%	+/- 6.9%	+/- 4.7%
Sample size	36	36	36	36
*based on 2006-2008 data from North Pipe Lake, Polk County, WI				

Conclusions

1. In this example, the effect of solar altitude on Secchi depth measurement variability over the May-September season was estimated to be +/- 7 percent. When including the effect of wind and surface reflection, the average measurement variability increased to +/- 12%. Some measurements would be expected to deviate as much as +/- 20%.
2. The example method above of using a solar altitude model and a viewscope is believed to largely eliminate the effect of solar altitude variation, the effect of waves and ripple, and the effect of blinding surface reflection. This example estimate is believe to be a conservative estimate because the example lake is protected from wind, and other external factors such as observer differences, disk color and reflectivity, and clouds and haze are not factored into the estimate.
3. Inconsistent procedures by lake monitors can introduce significant error into their lake's record of Secchi clarity data. For example, always monitoring early in the day (10 am) with no concern for the level of wind would be expected to produce one set of results. Then switching to a monitoring pattern of collecting data near 1 pm (highest solar altitude) but only if very little wind effect of waves and ripple is present would be expected to produce a larger magnitude set of results. But this difference would be unrelated to the water column transparency.

Acknowledgements

I wish to thank Bob Carlson (Kent State Secchi Dip-In), Gerrit Vershuur (solar altitude model originator), and Jeff Schloss (University of New Hampshire – Cooperative Extension) for their collaboration on this project.

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