TSI Model 3563 Integrating Nephelometer Operations Reference Manual

Written for use by the World Meteorological Organization (WMO)
Global Atmosphere Watch (GAW) Program

Patrick J. Sheridan and John A. Ogren

National Oceanic and Atmospheric Administration (NOAA)

Earth System Research Laboratory (ESRL)

Global Monitoring Division (GMD)

Boulder, Colorado 80305   USA

1 July 2014

Overview

This manual was written specifically for users of TSI Model 3563 integrating nephelometers. Its purpose is to ensure the quality of nephelometer measurements by 1) promoting standard operating procedures, 2) advising users of ways to optimize nephelometer performance and to recognize instrument problems, and 3) describing how to perform simple maintenance and repair procedures. This is not meant to be a comprehensive document in that all potential instrument problems are not addressed here, nor is it meant to be a replacement for the manufacturer's instrument manual "Instruction Manual: Model 3550/3560 Series Integrating Nephelometers". The most commonly encountered problems and maintenance procedures, however, are discussed here. This manual was written for field technicians of the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) program, so that a field reference document for instrument maintenance, repairs, and performance checks at remote field sites would be available. The hope is that comparable care for the instruments at different sites will lead to a similar high quality of nephelometer performance and reduced instrument down time for unscheduled maintenance and repairs.

Transporting the Nephelometer

Arrival of New Instrument from Factory

Initial Inspection

A Model 3563 integrating nephelometer arriving new from the TSI factory will most likely be in excellent condition. TSI ships these nephelometers in large wooden crates which are form-fitted with blown-in protective foam. Even with careful packing, however, some instrument components can loosen if the crate is handled roughly. Upon receipt of a new instrument, the following items should be inspected. This inspection will require the removal of the nephelometer photomultiplier and top covers.

- Photomultiplier Tubes (PMTs). *With the power cord disconnected*, open the PMT housing by removing the four PMT cover screws and remove the PMT cover. Reseat each PMT, wiggling the tube to ensure a good firm fit into the socket. TSI now puts a dab of silicone adhesive at the base of the PMT housings to fix them to the optical block base and prevent them from falling out during shipment. Older nephelometers did not have this adhesive applied. Even with the dab of adhesive on the PMT housings, however, they can still move sideways so that the light path might not be fully centered on the PMT window. *Afterwards, be sure to replace the PMT housing and tighten all four screws before connecting the power cord to the nephelometer. Applying power to the photomultiplier tubes with the PMT housing removed may permanently damage the PMTs*.

- Electrical and tubing connections. It is unlikely that any of the electrical or tubing connections would come loose during shipping, but it is a good idea to check them anyway. All of the cable-to-cable and cable-to-circuit board electrical connectors should be checked to make sure they are not loose. In addition, check for a firm connection on the electrical connector that joins the two circuit boards. The ½” Swagelok nuts between the HEPA zero air filter and the instrument body should be checked for tightness and the ¼” silicone tubing at the vent ports should also be checked to ensure that it is securely connected.

Model 3563 nephelometers are calibrated just before they leave the factory so it is not recommended to recalibrate the instrument unless a performance check suggests a problem with either the instrument or the calibration. As discussed in the sections below, there are several performance checks that should be performed on the new nephelometer to confirm proper operation.

Arrival of Working (Used) Instrument

The same initial inspection and performance checks should be performed as for new instrument arrival, except that some additional maintenance procedures and recalibration may be required. Refer to the Instruction Manual for detailed calibration instructions. For possible maintenance required, see Routine Maintenance and Special Maintenance sections of this document.

Shipping

Most users ship their TSI model 3563 nephelometers in the original wooden crate, although as the crates age it may be necessary to build a new crate or purchase an appropriate shipping container. With use the blown-in foam becomes broken, so some additional cushioning may also be required. The major criteria for fabricating a replacement shipping box for the nephelometer are:

- Protection. This is the most important criterion. The nephelometer is a rather heavy instrument with hard metal edges that can break through a flimsy shipping container. The shipping box should be made of a sturdy material; for example, wood, metal, or heavy plastic have all been used successfully. The box should have form-fitting or blown-in foam so that the instrument does not shift position in the box during transport or lifting. Cardboard and light plastic boxes should not be used because they provide a lesser degree of protection, they are easily damaged, and they require frequent replacement. Pieces of foam, newspaper, styrofoam peanuts, and other types of loose packing material should be avoided because they can allow the instrument to shift position inside the box. Whatever the final choice for a box or shipping container, it should be waterproof to keep out moisture.

- Weight and Dimensions. The wooden crates that the nephelometers are shipped from TSI in weigh approximately 61 kg (134 lbs.) when loaded with the nephelometer and accessory kit. If new shipping containers are constructed, keep in mind that several international delivery services (e.g., FedEx) have limits of 150 lbs. (68 kg) for standard air freight service. Larger packages are considerably more expensive to ship.

Finally, when shipping a TSI nephelometer make sure that the inlet and outlet are tightly sealed. This will eliminate the possibility of dust, packing debris, insects, etc., getting into the nephelometer and minimize the need for taking apart the instrument for cleaning. Also, it is wise to make sure the top and bottom covers and the PMT cover are tightly secured to protect sensitive and fragile instrument components.

Instrument Performance Checks

The TSI Model 3563 integrating nephelometer measures light scattering by aerosols at three visible wavelengths and over two ranges of angular integration. In order to determine the operating condition of a Model 3563 nephelometer, a set of performance checks should be performed. These permit the user to determine if maintenance and/or repairs are necessary, if recalibration of the instrument is warranted, or if adjustments should be made to potentially increase sensitivity. These performance checks are listed below.

Zero Baseline Measurement

The first of these performance checks is a series of instrument background checks on filtered air to determine the nephelometer baseline scattering values (i.e., the Air Rayleigh and wall scattering contributions that are subtracted from the total measured scattering to give the aerosol scattering coefficients). This 'zero baseline measurement' procedure is described in Chapter 3 of the TSI nephelometer manual. The scattering values obtained in the zero background measurements are available in the nephelometer 'Z' data records. The format of the Z data records is given in Chapter 6 of the nephelometer manual.

Two or more of these zero baseline measurements should be conducted in succession and the results should be consistent (i.e., the shift in the baseline measurements from one check to the next should be small – less than about 0.5 Mm^{-1} in each of the 6 channels. Consistency in the baseline values indicates that air leaks are not present in the nephelometer.

Span Gas Check

The second performance check is a check of the nephelometer calibration, also referred to as a 'span gas check'. In a span gas check, the scattering coefficients of a low span gas (typically filtered air) and a high span gas (for example, CO_2) are measured under instrument conditions of temperature and pressure. The results are used to derive the measured scattering coefficient of CO_2 under conditions of standard temperature and pressure (STP; 273.15K and 1013.25 mb). The measured value of scattering by pure CO_2 is compared with the published value [Anderson et al., 1996; Anderson and Ogren, 1998] for each measurement wavelength. The mean "error" in the CO_2 measurement (i.e., the difference from the CO_2 target value), calculated from each of the six nephelometer channels (three wavelengths each with a total and hemispheric backscatter measurement) should be within a few percent, with no individual channel's error being larger than 10%. If observed errors are larger than this, it suggests an instrument problem and/or a poor calibration, in which case repairs or recalibration may be necessary. A span gas check algorithm is provided in Appendix A so that users can perform these calculations. As discussed below, span gas checks should occur at regular intervals (e.g., weekly to monthly) so that instrument performance can be tracked over time.

Span gas checks that show large negative errors (e.g., -60% errors) are often caused by CO_2 either not entering the nephelometer as expected or not staying inside the instrument during the measurement. If the CO_2 is delivered under elevated pressure, hoses can be blown off fittings inside the nephelometer cover. Check to make sure no tubes have been disconnected or ruptured and that CO_2 is in fact flowing through the nephelometer. Since the CO_2 measurement is made relative to the measurement of filtered air, large negative errors will also be encountered if the filtered air measurement is compromised. This can happen if the zero filter ball valve is not completely sealing off the inlet and directing all air through the hepa filter. If this turns out to be the case, either adjust the ball valve so that it completely seals off the inlet, or else replace it if necessary.

Noise Check on Filtered Air

The third instrument performance check is a noise check on filtered air. For this check, a second hepa filter is required and should be mounted on the instrument inlet. Nephelometer data should be recorded using the Logging feature in the Data Collection module of the TSI Nephelometer software, or with any terminal emulation software. The nephelometer should be configured using the following commands (these are described in the Nephelometer Instruction Manual):

UE
STA60
STB30 (sufficient for a high flow rate like 30 lpm, should be longer for lower flow rates)
STP3600
STZ300
SMZ1
SP75
UD1
UZ1
UB

In this configuration, the nephelometer measures the scattering coefficient of filtered air for 54 minutes of each hour. There is a 5 minute zero baseline measurement period and two 30-second blanking periods. The noise check should be run for 12-24 hours to determine variability in the background values.

A program can then be run on this log file that calculates means and standard deviations for the 1-minute filtered air and zero background measurements. A Perl version of this program is included in Appendix B. As with the span gas checks, a noise check should be done periodically (a minimum of once a year) to check that instrument background values remain low and consistent. Typical ranges of the nephelometer performance statistics for the TSI 3563 nephelometers operated by the Global Monitoring Division of NOAA/ESRL (13 instruments) are shown below. Units for all values are Mm^{-1}.

	Mean	St. Dev.
Filtered Air, Total Scatter (all wavelengths):	0.01-0.10	0.10-0.40
Filtered Air, Backward Scatter (all wavelengths):	0.01-0.05	0.07-0.30
Neph. Background, Total Scatter (all wavelengths):	2-10	0.02-0.12
Neph. Background, Backward Scatter (all wavelengths):	1-10	0.01-0.12

Values observed that are far beyond the upper end of these ranges suggest an instrument problem; additional inspection of nephelometer is suggested.

Performance check timetable

In order to track the performance of a nephelometer, records should be kept of diagnostic measurements over time. This is the best way to determine if the performance of your nephelometer has changed. Measurements and checks that should be recorded and monitored over time include:

- Span gas checks (weekly to monthly)
- Overnight noise checks (at least yearly)
- Zero Background checks (hourly to daily)
- Lamp current and voltage (continuous)
- Nephelometer temperature, pressure, and relative humidity (continuous)

The rationale for doing span gas and overnight noise checks has already been discussed. Zero background checks show when the instrument background changes, and are especially useful in showing when the inside of a nephelometer is getting dirty. The monitoring of lamp current and voltage is necessary because lamps that are aging lose brightness and begin to draw more current. If the lamp draws too much current, the analog circuit board could be damaged. We recommend replacing the lamp when the lamp current rises over 7 amps. Temperature, pressure and relative humidity measurements are required for interpretation of nephelometer measurements, and are also useful in diagnosing many potential instrument problems.

Check of Nephelometer Raw Photon Count Rates

A detailed discussion of the nephelometer theory of operation is available in Chapter 7 of the TSI Model 3563 Instrument Manual which shows all of the calculations used by the nephelometer to convert the raw signals into scattering coefficients. The manual goes into considerable detail telling how the raw signals are acquired, but no information is provided on what acceptable ranges are for these raw signals and how they can be used to evaluate system performance. An objective of this document is to provide some guidance, based on our experience with a large number of TSI Model 3563 nephelometers, on how to evaluate nephelometer performance and diagnose common nephelometer problems based on the raw photon counts.

Figure 7-2 in the TSI nephelometer manual shows a schematic drawing of the reference chopper. The chopper spins and makes a full rotation 23 times per second. The chopper wheel is divided into three sectors; these are labelled 'CAL', 'SIGNAL', and 'DARK'. The CAL sector is translucent and covers 80 degrees of the circle. The SIGNAL sector covers 180 degrees of the circle and is open (i.e., no chopper material is in this sector). The DARK sector is black and covers the final 100 degrees of the circle.

The position of the chopper wheel determines into which bin the raw photon counts are placed. When the CAL sector (i.e., the calibrator) is exposed to the light source, a fraction of the incident light passes through it to the photomultiplier tubes (PMTs). The calibrator is supposed to be a 'fixed-brightness object', which is used to relate a measured amount of photon counts to a known amount of light scattering. Unfortunately, the calibrator brightness is not truly fixed. Its brightness changes over time due to particle deposition and aging, and this is one of the main reasons (along with PMT sensitivity changes) for having to recalibrate the nephelometer. When the SIGNAL sector is in position, the chopper passes photons scattered from particles and gases inside the scattering volume unaltered to the PMTs. Any deposited particles or fibers in the optical path (e.g., on the dark trap mirror, on the edge of apertures, etc.) may also contribute to the SIGNAL counts. The DARK sector does not pass light, and photon counts detected during this part of the chopper cycle represent PMT background noise.
An example of the raw photon count rates for the various color channels and chopper positions with the nephelometer measuring filtered air is shown in Table 1. For diagnostic purposes, it is preferable to have the nephelometer filled with filtered air so the variability due to particles is eliminated. These data were taken from one of the NOAA nephelometers currently in operation at a global monitoring station. The count rates are approximate since the signals bounce around but are representative.

Table 1. Example of TSI nephelometer photon count frequency (Hz) on filtered air.

	Total Scatter			**Backscatter**		
Color	**Calibrate**	**Signal**	**Dark**	**Calibrate**	**Signal**	**Dark**
Blue	145000	1780	35	89000	890	26
Green	126000	1040	10	78000	540	6
Red	159000	1260	235	99000	820	221

The photon count rates presented in this table are also used in the span gas check calculations shown in Appendix A to determine the nephelometer sensitivity factors, defined as the photon count rate (Hz) attributable to Rayleigh scattering by air at STP. Long-term trends in the wavelength-specific sensitivity factors should be monitored for degradation of phototube sensitivity.

As a general strategy, nephelometer users should try to optimize their instruments so that the magnitude of the CAL (Calibrate) and SIGNAL photon frequencies are maximized while keeping the DARK counts at an acceptable level. For this discussion we will focus on the 'Total Scatter' channels, which contain the photon counts recorded when the backscatter shutter is out of the optical path. Plots of typical photon count rate vs. voltage curves for PMTs are available in the literature and have not been reproduced here. A PMT has a threshold voltage below which there are no counts detected. Above this threshold voltage the count rates increase rapidly until they reach a plateau region, where further increases in supply voltage result in diminishing increases in photon count rate. At some point in the plateau region the PMT noise (i.e., the DARK count rate) also starts to increase and operation of the PMTs at very high voltages leads to shorter PMT lifetimes. Therefore we try to optimize PMT voltages such that they are as low as possible with plateaued CAL (and SIGNAL) count rates. The way to do this is to pick a relatively low PMT voltage (e.g., 900V) to start and record the total scatter CAL, SIGNAL and DARK count rates, with the instrument filled with filtered air. Averaging the raw photon count rates over a longer period of time (e.g., 30-60 sec) is helpful in viewing the values for each supply voltage as the numbers will not jump around so much. The TSI nephelometer software package has a function that permits viewing of a user-selectable running average of the count rates. After the photon count rates are recorded, the PMT voltage should be increased by 25V or 50V and the new values observed and recorded. At some point the photon counts will not increase much with increasing supply voltage (the point of diminishing returns). At this point the PMT count rate has plateaued and the voltage should be decreased to the setting of the last large count rate increase. The TSI nephelometer will supply a maximum of 1200V to each PMT. If a PMT needs to operate above 1150V to achieve adequate photon count rates in a nephelometer with other parts of the optical system in good working order, it is likely that the PMT will need to be replaced soon and a replacement PMT should be ordered.

The CAL photon count rates are affected by a number of factors, including lamp brightness, light pipe transmission, calibrator properties, color filter properties, photomultiplier (PMT) alignment, and PMT sensitivity. For a nephelometer in good working condition with a new lamp, raw photon counts on filtered air should be at least BLUE=80000 Hz, GREEN=100000 Hz and RED=100000 Hz for the TS (total scatter)-CAL values. The TS_CAL values track the brightness of the chopper calibrator sector. Lower count rates in any channels may suggest one or more of several possible problems, including a weak or failing lamp, an aging light pipe, a dirty calibrator surface, a dirty or hazy color bandpass filter, a misaligned PMT, or an old PMT with reduced sensitivity. Low TS-CAL count rates lead to higher variability in span gas calibration checks, and in order to minimize this we try to maximize the TS-CAL photon count rates. In the example shown in Table 1, all of the TS-CAL count rates are considered acceptable.

If all color channels show low TS-CAL count rates, the problem may be an aging or weak lamp. The lamp should be replaced with a new one and the count rates observed to see if they have increased. If they have not, the other potential problems should be investigated, although these typically do not simultaneously affect all of the color channels. One problem that can be observed after shipping is one or more PMT's being tilted off the optical path. To check this, the PMT cover must be removed. With no power to the nephelometer (and just to be sure disconnect the power cord), the PMT cover should be opened and the seating of the PMTs in their sockets should be checked. PMTs can become tilted well off the optical axis after shipping or rough handling and this could significantly decrease the photon count rates. Re-seat the PMTs by pressing them downward into their sockets and replace the PMT housing cover. Only after the cover has been re-installed should power be turned on to the instrument. Applying power to the PMTs with the PMT housing cover removed can result in permanently damaged PMTs.

Photomultiplier tubes will lose sensitivity over time (typically over many years), and they should be replaced when necessary. It is a good idea to keep a spare set of tubes on hand in case a replacement is necessary. This is an easy replacement and one of the first things to check if a nephelometer is displaying low counts.

Degradation of the color bandpass filters or light pipe can also lead to lower photon count rates. The color bandpass filters can become hazy over time because of a deterioration of the surface coating. This is a relatively rare occurrence with our nephelometers, but may be more common in some environments (e.g., coastal marine) than others. The bandpass filters can be examined visually for a hazy appearance, but the only sure way to tell if a filter is not passing enough photons is to compare it with a new one. A comparison of the photon count rates through an old and new color bandpass filter should tell you if the old one has deteriorated. If the color bandpass filter is not passing enough photons, it should be replaced with a new filter. While this test implies that a spare set of color filters should be purchased and kept on hand, the recommendation here is that this is not necessary unless there is reason to suspect that the bandpass filter is the problem (i.e., tests performed on other parts of the optical system show properly working components).

The nephelometer light pipe transmits light from the lamp through the instrument body wall into the interior scattering volume. The light pipe is constructed of a clear glass tube onto which a thin opal glass diffuser is glued. The two pieces are glued together using a clear optical adhesive of the proper refractive index. Over time, the intense light and heat from the lamp ages the glue to a brownish color, so that the light passing through the light pipe looks slightly orange instead of bright white. The reason the transmitted light looks orange is because the shorter wavelengths (blues, and to a much lesser extent greens) are preferentially absorbed by the aged glue. In nephelometers with a degraded light pipe but with all other optical system components in good condition, the TS-CAL count rates for BLUE might not exceed 20000 Hz while the GREEN values may be only slightly low and the RED values in the normal range. In our experience, light pipe degradation occurs in the older nephelometers with 15 or more years of continuous service.

The example below illustrates this situation for a nephelometer at our South Pole, Antarctica station in 2010. In this case the TS-CAL photon count rates for BLUE, GREEN, and RED were 17 kHz, 61 kHz, and 95 kHz, respectively. These values indicate that the RED count rate was very close to normal, the GREEN rate was low, and the BLUE rate was extremely low. A plot of the 1-

minute nephelometer data from this period is shown in Figure 1. Even though the TS-CAL GREEN count rate is lower than that considered optimal for a nephelometer in good working condition, the signal noise was not appreciably affected. The noise in the BLUE TS-CAL signal is primarily due to the low BLUE photon count rate, since all other components of the optical system were checked and found to be working properly. A repair of the light pipe increased the BLUE count rate substantially and the GREEN count rate moderately (both increased to 80-90 kHz), and the large noise of the BLUE scattering trace was eliminated.

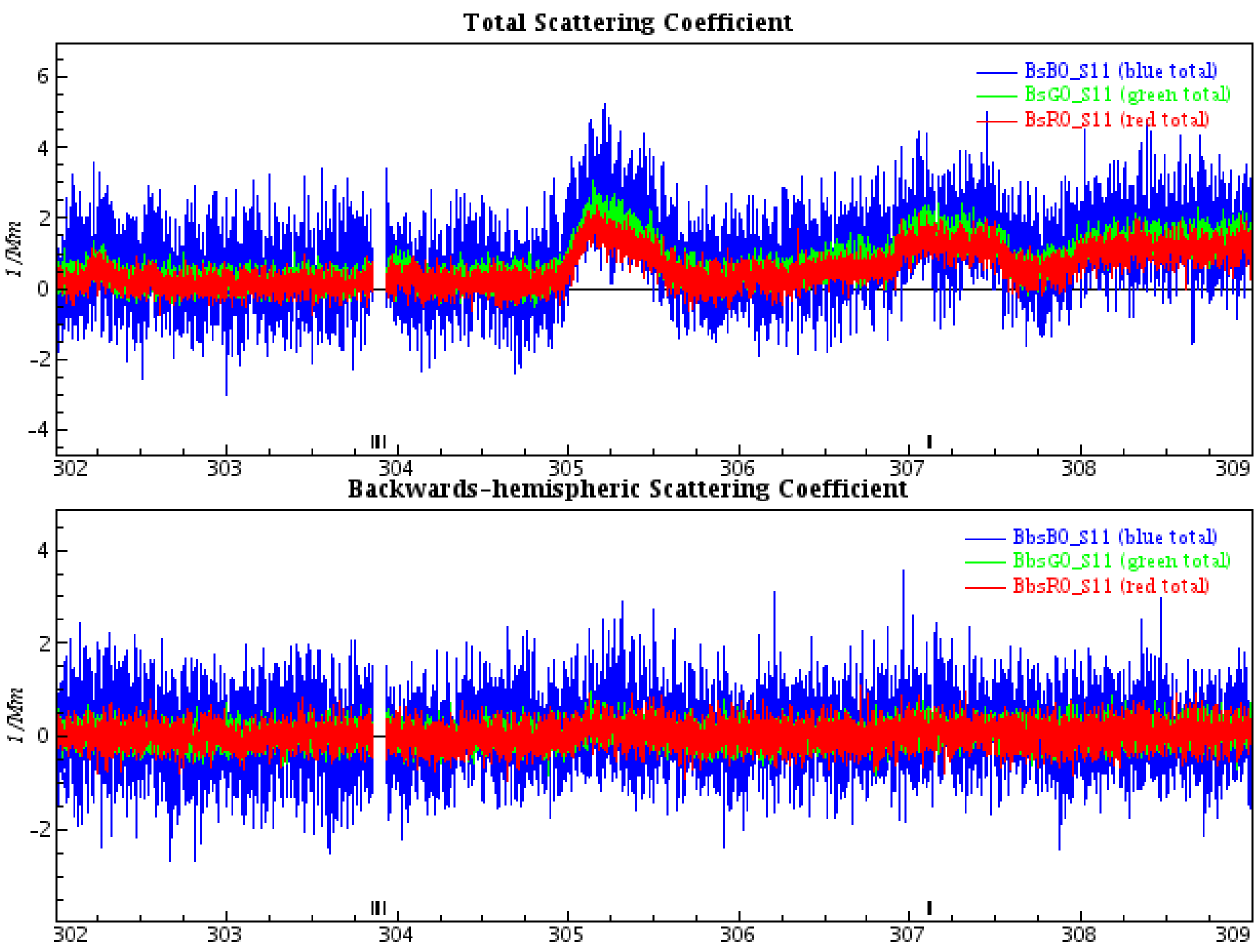

Figure 1. TSI Model 3563 nephelometer displaying noisy signal due to very low blue photon count rates at South Pole, Antarctica. X-axis shows day of the year, 2010.

These data suggest that the BLUE=80 kHz, GREEN=100 kHz and RED=100 kHz recommendations for TS-CAL count rates should be considered guidelines (and targets to aim for) rather than absolute minimum acceptable values for nephelometer operation. The issue really becomes the level of noise you are willing to tolerate in the signal. In the example above, a count rate of TS-CAL (GREEN) = 61 kHz did not show an overly noisy signal, and span gas checks during this time showed reasonable errors in the green channels (i.e., the nephelometer was measuring GREEN scattering accurately). The BLUE scattering signal, however, was much more noisy than

GREEN or RED and it is clear that a TS-CAL (BLUE) photon count rate of 17 kHz is not acceptable for nephelometer operation at 1-minute data resolution.

The TS-SIGNAL counts depend not only on the other factors listed above, but also on air density and the presence of aerosol particles in the scattering volume. The TS-SIGNAL values will then vary with elevation above sea level due to the relationship of Rayleigh scattering with air density. The TS-DARK counts provide a measure of the PMT noise. A good way to gauge nephelometer performance is to look at the (TS-SIGNAL – TS-DARK) count rates on filtered air for the various color channels. A properly working nephelometer should show 'SIGNAL – DARK' count rates of at least a few hundred Hz (>400 Hz is typical on filtered air at sea level). The BLUE and GREEN channels should have very low DARK counts (< ~40 Hz). The RED channel always shows higher DARK counts (100-400 Hz are typical) because the RED PMT is sensitive into the near–IR and detects heat. Therefore, if the TS-RED DARK counts are 300 Hz, you would want to see the TS-RED SIGNAL counts at or above 700 Hz.

There are a few scenarios where the TS-SIGNAL count rates are far higher than normal, while the TS-CAL and TS-DARK count rates remain in the normal range. A situation where this could occur is if the nephelometer has liquid water in it, potentially from rain entering an inlet, condensation in the inlet line, or a leak from an upstream humidifier. Liquid water reflects a lot of light from the dark trap area (due to standing water or drops on the dark trap mirror) and generally the TS-SIGNAL count rates increase to several thousand Hz. If this happens the nephelometer would need to be opened, cleaned and dried out. Dead insects such as flies, gnats, moths, etc., can also reflect large amounts of light. Spiders, in particular, cause issues because their webs in addition to their bodies can reflect light and cause extremely high SIGNAL photon counts. If the spider is alive in the nephelometer the SIGNAL count rates can vary widely depending on the spider's position in the optical path. Again, this situation would require opening the instrument, removing the spider and cleaning the internal surfaces.

While there is no agreed upon method for troubleshooting a nephelometer that displays low photon counts, we recommend, based on our experience with many nephelometers, checking/replacing components in the following order. Many of these procedures are described in detail in Chapter 8 of the TSI Nephelometer Manual.

1) Replace the lamp. Aged lamps draw more current than new ones and put out less light. A lamp is the easiest component in this list to replace and one of the more likely contributors to the problem.
2) Reseat photomultiplier tube(s). <u>Done only with the power cord disconnected</u>. Especially necessary after shipping the instrument.
3) Adjust/optimize photomultiplier tube voltages to get maximum photon count rates.
4) Clean the light pipe lens (interior surface inside the instrument).
5) Inspect/clean the calibrator sector of the chopper wheel. This should be done using high-purity alcohol, taking care not to scratch or leave a residue on the optical surface.
6) Replace photomultiplier tube(s). <u>Done only with the power cord disconnected</u>.

7) Inspect color bandpass filter(s). If hazy appearance, replace with new filter(s). Compare count rates on old and new filters. If new filter(s) are not showing higher count rates, remove and put the old filter(s) back in because they were not the problem.
8) Remove and repair light pipe.

Calibrations

The nephelometer is calibrated by relating a known amount of scattering (e.g., the Rayleigh scatter of filtered air or CO_2 at one of the nephelometer wavelengths) to a measured count rate of scattered photons. Calibrations can drift over time due to changing conditions of the calibrator section of the chopper blade or shifting sensitivity of the PMTs, and at some point a re-calibration of the nephelometer may become necessary. As discussed previously, a span gas check is a good way to spot drifting calibrations. Detailed instructions on how to calibrate the nephelometer are given in Chapter 4 of the Model 3550/3560 Series Integrating Nephelometer Instruction Manual. Calibration should be performed only when a span gas check or instrument comparison suggests that a nephelometer's calibration has shifted. Routine re-calibration is not recommended as long as regular span gas checks are performed. The TSI nephelometer software displays the K2 and K4 constants determined in each calibration. The K2 constant is a measure of how much light is being detected by each PMT during the calibration portion of each chopper cycle. This value can vary over a fairly wide range depending on the condition of the chopper shutter. Typical values for K2 for all three wavelengths in a properly functioning nephelometer are 2E-3 to 8E-3, although it is possible that values for a particular nephelometer could lie slightly outside this range. The K4 constant is related to the fraction of the scattering volume illuminated during the backscatter measurement. Typically, the value of this constant is near 0.5.

After a calibration has been performed, it is always a good idea to perform a span gas check to see how well the nephelometer measures a quantity with a known scattering value. If the span check errors are large, a repeat of the calibration may be necessary. Alternatively, the full calibration procedure can be repeated until reproducible values of the K2 and K4 constants are achieved.

Routine Maintenance

Maintenance procedures for the nephelometer are described in Chapter Eight of the TSI Nephelometer Instruction Manual. Most of these procedures are recommended to be done "as needed" or "periodically". Some need to be performed when the diagnostic measurements suggest it is time for maintenance. Details on how to do the maintenance procedures can be found in the nephelometer manual. Users with specific questions on maintenance procedures can contact the authors for assistance.

Routine maintenance procedures are relatively simple to perform and include:

- Replacement of particulate filters (yearly, more frequently at very dusty or polluted sites)
- Replacement of the fan filter (inspect yearly)
- Replacement of lamp (as needed, generally 2-3 times per year)
- Checking for instrument leaks (yearly)
- Cleaning the main cavity of the nephelometer (as needed, if instrument background goes above ~ 10 Mm^{-1})
- Cleaning or changing the flocked paper (when main cavity is cleaned)
- Cleaning the light pipe lens (when main cavity is cleaned)
- Cleaning the dark trap mirror (when main cavity is cleaned)
- Calibration or replacement of the T, P, and RH sensors (check annually)

In general, we have found that cleaning the nephelometer interior annually is sufficient except in very dirty, dusty or salty environments.

Special Maintenance

Special maintenance procedures should be performed on an “as needed” basis. These procedures are often on sensitive components of the nephelometer, so extra care should be exercised when working on these procedures. Special maintenance procedures include:

- Cleaning or replacement of aged bandpass filters
- Adjustment or replacement of PMTs
- Cleaning or replacement of old/scratched chopper shutter
- Replacement of IC board processors and chips
- Replacement of chopper and backscatter shutter motors
- Adjustment/replacement of IR reflective diodes
- Cleaning of the backscatter shutter
- Replacement or realignment of the zero filter ball valve
- Repair/replacement of the light pipe

The two IR reflective diodes are used to detect when the zero valve and the chopper shutter are in the appropriate positions. The lenses for these diodes can get dirty and may need to be cleaned periodically. Also, small bits of lint or dirt can get lodged in the window recesses and partially or completely block the sensors. These diodes have been found to fail over time, so when cleaning or adjustment does not make these perform better, it is time for a new diode.

The backscatter shutter should be cleaned so that dirt or dust on the shutter does not lead to additional scattering of light from the lamp. Care should be taken not to change the orientation of the backscatter shutter (i.e., the angle at which it rotates). If this orientation is changed, the K4 constant will change and a new calibration will be required.

Over time, the ball valve assembly can cause problems either by developing a misalignment or by becoming more difficult to turn. These problems can cause background measurements that are off by varying degrees, or in the extreme case of a ball valve that will not turn a nephelometer unable to calculate its own backgrounds. A misaligned ball valve can allow ambient air (containing particles) into the instrument during the zero air background measurement, which obviously compromises the background measurement. This problem can be observed by shining a flashlight into the nephelometer inlet when the valve is supposed to be in the zero air position. Seeing a gap at the edge of the opening where air can get directly into the nephelometer confirms the problem.

A misalignment of the ball is usually caused by one or more of the four set screws that hold the couplers in place becoming loose. This permits the shaft to rotate relative to the aluminum flange that is used a positioning device. The way to correct this problem is to loosen all of the set screws so that the ball can be turned by hand. Position the ball so that it is as far open as possible; i.e., that it allows air to enter the nephelometer as efficiently as possible. Then position the flange so that its edge is directly over the IR reflective diode sensor that determines flange (and valve) position. The metal should be 1-3 mm away from the sensor. If the distance is greater than that, adjust the position of the IR reflective diode closer to the aluminum flange. After aligning the ball and getting the flange in the correct position, tighten the set screws to lock the assembly in place. Make sure when the ball valve changes position during background checks that the ball is also in the proper (sealed) position at that time.

In the extreme case, an aged ball valve can become locked in position and the shaft will either break or the motor or coupling will be damaged. Replacement of the ball valve is discussed in the next section.

<u>Repairs</u>

Nephelometer repairs can be tricky and in general are best left to the factory. Repairs of this type include electronic repairs, circuit board repairs, motor repairs, etc. There are a few repairs that can usually be made by a competent end user. These include:

- Replacement of broken zero filter motor, ball valve, or coupler
- Repair or replacement of ribbon cables and connectors
- Replacement of white rectangular plastic AMP connectors and attached cables

If the ball valve is not turning easily, it probably needs to be replaced. This ball valve can be ordered from TSI, but can also be ordered directly from the manufacturer. The manufacturer is Georg Fischer Piping Systems. The valve is a “Ball Valve Type 346” with a 1-inch bore. See the web page at http://www.us.piping.georgefischer.com/index.cfm?6330B9B99D5F474C87D47549DE959C77

This valve is now out of production, but the manufacturer states that it will be supported with parts for at least 10 years (starting Dec. 2004). If you have a broken ball and/or stem, you can simply order another ball set. The part number you will need is 161.482.877. If you need a new ball valve (including the valve body), you will need part number 161.483.943.

To replace the broken valve, loosen the 4 large hex-head bolts that secure the valve and inlet housing to the nephelometer body. Remove the broken valve, inlet housing, and hepa filter. Remove the coupling and flange from the shaft of the broken valve and install it on the shaft of the new valve. Make sure to align the set screws with the groove in the shaft so that the ball position will be correct. Place the new ball valve in position, making sure that the couplers fit together and that the flange is close to the IR reflective diode sensor. Tighten the four hex-head bolts down to secure the ball valve. CAUTION: The ball valve body has o-ring seals at each end, so the bolts do not have to be tightened really tight. The o-rings have to be compressed, but over-tightening the bolts can impede the turning of the ball in the valve.

Replacement of the zero filter motor assembly should be straightforward – just a one-for-one replacement. Again, make sure that the couplers fit together and that the ball is aligned after the replacement.

NOAA Instrument Modifications and Software

NOAA makes several modifications to the standard TSI nephelometer. These include:

- installing plastic clips to hold the circuit boards together
- installing star washers on the 4 large bolts that hold down the ball valve assembly to prevent them from slipping
- replacing fan covers with a large speaker grill, and removing the metal strip down the middle of the cutout so the lamp can be changed without removing nephelometer cover
- installation of a small solenoid valve on the ¼-inch port fitting next to the lamp shield and installation of a second BNC-style connector on the communications power/communications panel so that the solenoid valve can be controlled remotely for automated span gas checks
- cutting the nephelometer top cover lengthwise so that it can be removed without having to remove inlet and outlet plumbing

If details are desired regarding any of these modifications, please contact one of the authors.

References

Anderson, T.L., Covert, D.S., Marshall, S.F., Laucks, M.L., Charlson, R.J., Waggoner, A.P., Ogren, J.A., Caldow, R., Holm, R.L., Quant, F.R., Sem, G.J., Wiedensohler, A., Ahlquist, N.A., and Bates, T.S. (1996) Performance characteristics of a high-sensitivity, three-wavelength, total scatter/backscatter nephelometer. **J. Atmos. Oceanic Technol. 13**, 967-986.

Anderson, T.L., and Ogren, J.A. (1998) Determining aerosol radiative properties using the TSI 3563 nephelometer. **Aerosol Sci. Technol. 29**, 57-69.

Appendix A: Span check algorithm for TSI 3563 Nephelometer

A. Configuration commands.

UE
STA60
STB30 (sufficient for a high flow rate like 30 lpm, should be longer for lower flow rates)
STP3600
STZ300
SMZ1
SP75
UD1
UZ1
UY1
UT1
UP3
VZ
UB

B. Procedure

Flush with air for 3-5 minutes at ~ 30 lpm
Turn off blower, close off output, restrict input if possible.
Flush with CO_2 for 10 minutes at ~ 5 lpm
Measure with CO_2 for 5 minutes at ~ 5 lpm
Record average values during CO_2 measurement
Open input and output fully, turn on blower
Flush with air for 3-5 minutes at ~30 lpm
Measure with air for 10 minutes at ~ 30 lpm
Record average values during air measurement
Perform a zero

C. Data logging

Average values of the following nephelometer parameters should be recorded for the CO_2 and AIR measurements. Separate values are recorded for the blue, green, and red channels [λ] in most cases.

Photon Count Records (B, G, R):

- NTCAL[λ]: photon counts from calibrator (total scatter)
- NTMEAS[λ]: photon counts from measure (total scatter)
- NTDARK[λ]: photon counts from dark (total scatter)
- REVT: revolutions of chopper for total scatter measurement
- NBCAL[λ]: photon counts from calibrator (back scatter)
- NBMEAS[λ]: photon counts from measure (back scatter)

– NBDARK[λ]: photon counts from dark (back scatter)
– REVB: revolutions of chopper for backscatter measurement

Data Records (D):
– BSP[λ]: total scattering coefficient (m^{-1})
– BBSP[λ]: back scattering coefficient (m^{-1})

Auxiliary Status Records (Y):
– PRES: barometric pressure (hPa)
– TEMP: sample temperature (K)
– T-IN: inlet temperature (K)
– RH: relative humidity (percent)
– VLAMP: lamp voltage (V)
– ALAMP: lamp current (A)

C. Data reduction

The calculations use the following constants:
Standard temperature and pressure:
T_STP = 273.15 K
P_STP = 1013.25 hPa
Rayleigh scattering coefficient of air at STP:
BSGAIR[λ] = (27.89, 12.26, 4.605) Mm^{-1} for (450, 550, 700) nm wavelength
BBSGAIR[λ] = BSGAIR[λ] / 2
Rayleigh scattering coefficient of CO2, relative to air:
RAYCO2 = 2.61
Rayleigh scattering coefficient of CO2 at STP:
BSGCO2TRUE[λ] = BSGAIR[λ] * RAYCO2
BBSGCO2TRUE[λ] = BSGCO2TRUE[λ] / 2
chopper rotation rate = 22.994 revolutions per second
chopper gate widths = (40, 60, 140) degrees for (calibrate, dark, signal) sections

Calculate average gas density and lamp power:
DENAIR = PRES[AIR] / TEMP[AIR] *273.15 / 1013.25
DENCO2 = PRES[CO2] / TEMP[CO2] *273.15 / 1013.25
POWER = VLAMP * ALAMP

Convert photon counts to count rates in Hz (eq. 7-15 in TSI manual), for CO2 and AIR measurements separately:
HZTCAL[λ] = NTCAL[λ] * (360/40) * 22.994 / REVT
HZTMEAS[λ] = NTMEAS[λ] * (360/140) * 22.994 / REVT
HZTDARK[λ] = NTDARK[λ] * (360/60) * 22.994 / REVT
HZBCAL[λ] = NBCAL[λ] * (360/40) * 22.994 / REVB
HZBMEAS[λ] = NBMEAS[λ] * (360/140) * 22.994 / REVB

HZBDARK[λ] = NBDARK[λ] * (360/60) * 22.994 / REVB

Don't bother with dead time correction (eq. 7-16 in TSI manual), because count rates on CO2 and air are too low for dead time to matter.

Calculate CO2 Rayleigh scattering at STP, as measured by nephelometer:
BSGCO2[λ] = BSPCO2[λ] / DENCO2 - BSPAIR[λ] / DENAIR + BSGAIR[λ]
BBSGCO2[λ] = BBSPCO2[λ] / DENCO2 - BBSPAIR[λ] / DENAIR + BSGAIR[λ]/2

Calculate percentage error in measured CO2 Rayleigh scattering:
ERRTS[λ] = (BSGCO2[λ] / BSGCO2TRUE[λ] - 1) * 100
ERRBS[λ] = (BBSGCO2[λ] / BBSGCO2TRUE[λ] - 1) * 100

Calculate nephelometer sensitivity factor, defined as the photon count rate (Hz) attributable to Rayleigh scattering by air at STP:
SENSTS[λ] = ((HZTMEASCO2[λ] - HZTDARKCO2[λ]) / DENCO2
- (HZTMEASAIR[λ] - HZTDARKAIR[λ]) / DENAIR)
/ (RAYCO2 - 1)
SENSBS[λ] = ((HZBMEASCO2[λ] - HZBDARKCO2[λ]) / DENCO2
- (HZBMEASAIR[λ] - HZBDARKAIR[λ]) / DENAIR)
/ (RAYCO2 - 1)

Absolute values of ERRTS[λ] and ERRBS[λ] larger than a few percent indicate a potential problem with the nephelometer or with the calibration parameters stored within the nephelometer. If larger errors are encountered, the span check should be repeated. If the errors persist, the full calibration procedure recommended by TSI should be performed.

Long-term trends in SENSTS[λ] and SENSBS[λ] should be monitored for degradation of phototube sensitivity.

Appendix B: Evaluation of nephelometer noise levels from overnight zero-air runs

Program to calculate nephelometer statistics (mean and standard deviation of the filtered air and zero background measurements for all six channels).

(start of program)

```
#!/usr/bin/perl
# Name: nephstat
# Desc: calculate performance statistics from a raw neph data file
# Call: nephstat infile [ > outfile ]
# Uses: data file written by TSI neph software
#  OUT: standard output
#  Rev: 970529 JAO translate awk version to perl

eval '$'.$1.'$F[1];' while $ARGV[0] =~ /^([A-Za-z_0-9]+=)(.*)/ && shift;
                  # process any FOO=bar switches

  $xBtsBair = 0;  $xxBtsBair = 0;
  $xBtsGair = 0;  $xxBtsGair = 0;
  $xBtsRair = 0;  $xxBtsRair = 0;
  $xBbsBair = 0;  $xxBbsBair = 0;
  $xBbsGair = 0;  $xxBbsGair = 0;
  $xBbsRair = 0;  $xxBbsRair = 0;
  $xBtsBbkg = 0;  $xxBtsBbkg = 0;
  $xBtsGbkg = 0;  $xxBtsGbkg = 0;
  $xBtsRbkg = 0;  $xxBtsRbkg = 0;
  $xBbsBbkg = 0;  $xxBbsBbkg = 0;
  $xBbsGbkg = 0;  $xxBbsGbkg = 0;
  $xBbsRbkg = 0;  $xxBbsRbkg = 0;
  $nAir = 0;      $nBkg = 0;

 while (<>) {
    tr/\n\r//d;               # strip record separator
    @F = split(",");          # split input line on commas

    if (/^D,N/) {       # normal data records
      $xBtsBair += $F[3];  $xxBtsBair += $F[3] * $F[3];
      $xBtsGair += $F[4];  $xxBtsGair += $F[4] * $F[4];
      $xBtsRair += $F[5];  $xxBtsRair += $F[5] * $F[5];
      $xBbsBair += $F[6];  $xxBbsBair += $F[6] * $F[6];
      $xBbsGair += $F[7];  $xxBbsGair += $F[7] * $F[7];
      $xBbsRair += $F[8];  $xxBbsRair += $F[8] * $F[8];
      $nAir += 1;
    }
    if (/^Z/) {               # zero records
      $x = $F[1] - $F[7];     $xBtsBbkg += $x;  $xxBtsBbkg += $x * $x;
      $x = $F[2] - $F[8];     $xBtsGbkg += $x;  $xxBtsGbkg += $x * $x;
      $x = $F[3] - $F[9];     $xBtsRbkg += $x;  $xxBtsRbkg += $x * $x;
      $x = $F[4] - $F[7]/2;   $xBbsBbkg += $x;  $xxBbsBbkg += $x * $x;
      $x = $F[5] - $F[8]/2;   $xBbsGbkg += $x;  $xxBbsGbkg += $x * $x;
      $x = $F[6] - $F[9]/2;   $xBbsRbkg += $x;  $xxBbsRbkg += $x * $x;
      $nBkg += 1;
    }
  }   # end while
```

```
# print out statistics

  $aBtsBair = $xBtsBair / $nAir; $sBtsBair = sqrt( $xxBtsBair / $nAir - $aBtsBair**2 );
  $aBtsGair = $xBtsGair / $nAir; $sBtsGair = sqrt( $xxBtsGair / $nAir - $aBtsGair**2 );
  $aBtsRair = $xBtsRair / $nAir; $sBtsRair = sqrt( $xxBtsRair / $nAir - $aBtsRair**2 );
  $aBbsBair = $xBbsBair / $nAir; $sBbsBair = sqrt( $xxBbsBair / $nAir - $aBbsBair**2 );
  $aBbsGair = $xBbsGair / $nAir; $sBbsGair = sqrt( $xxBbsGair / $nAir - $aBbsGair**2 );
  $aBbsRair = $xBbsRair / $nAir; $sBbsRair = sqrt( $xxBbsRair / $nAir - $aBbsRair**2 );
  $aBtsBbkg = $xBtsBbkg / $nBkg; $sBtsBbkg = sqrt( $xxBtsBbkg / $nBkg - $aBtsBbkg**2 );
  $aBtsGbkg = $xBtsGbkg / $nBkg; $sBtsGbkg = sqrt( $xxBtsGbkg / $nBkg - $aBtsGbkg**2 );
  $aBtsRbkg = $xBtsRbkg / $nBkg; $sBtsRbkg = sqrt( $xxBtsRbkg / $nBkg - $aBtsRbkg**2 );
  $aBbsBbkg = $xBbsBbkg / $nBkg; $sBbsBbkg = sqrt( $xxBbsBbkg / $nBkg - $aBbsBbkg**2 );
  $aBbsGbkg = $xBbsGbkg / $nBkg; $sBbsGbkg = sqrt( $xxBbsGbkg / $nBkg - $aBbsGbkg**2 );
  $aBbsRbkg = $xBbsRbkg / $nBkg; $sBbsRbkg = sqrt( $xxBbsRbkg / $nBkg - $aBbsRbkg**2 );

  printf "Total\tFiltered Air\tMean\tBlue\t%8.3f\t1/Mm\n",  $aBtsBair*1E6;
  printf "Total\tFiltered Air\tMean\tGreen\t%8.3f\t1/Mm\n", $aBtsGair*1E6;
  printf "Total\tFiltered Air\tMean\tRed\t%8.3f\t1/Mm\n",   $aBtsRair*1E6;
  printf "Back\tFiltered Air\tMean\tBlue\t%8.3f\t1/Mm\n",   $aBbsBair*1E6;
  printf "Back\tFiltered Air\tMean\tGreen\t%8.3f\t1/Mm\n",  $aBbsGair*1E6;
  printf "Back\tFiltered Air\tMean\tRed\t%8.3f\t1/Mm\n",    $aBbsRair*1E6;
  printf "Total\tFiltered Air\tStdDev\tBlue\t%8.3f\t1/Mm\n",      $sBtsBair*1E6;
  printf "Total\tFiltered Air\tStdDev\tGreen\t%8.3f\t1/Mm\n",     $sBtsGair*1E6;
  printf "Total\tFiltered Air\tStdDev\tRed\t%8.3f\t1/Mm\n", $sBtsRair*1E6;
  printf "Back\tFiltered Air\tStdDev\tBlue\t%8.3f\t1/Mm\n", $sBbsBair*1E6;
  printf "Back\tFiltered Air\tStdDev\tGreen\t%8.3f\t1/Mm\n",      $sBbsGair*1E6;
  printf "Back\tFiltered Air\tStdDev\tRed\t%8.3f\t1/Mm\n",  $sBbsRair*1E6;
  printf "Total\tBackground\tMean\tBlue\t%8.3f\t1/Mm\n",    $aBtsBbkg*1E6;
  printf "Total\tBackground\tMean\tGreen\t%8.3f\t1/Mm\n",   $aBtsGbkg*1E6;
  printf "Total\tBackground\tMean\tRed\t%8.3f\t1/Mm\n",           $aBtsRbkg*1E6;
  printf "Back\tBackground\tMean\tBlue\t%8.3f\t1/Mm\n",           $aBbsBbkg*1E6;
  printf "Back\tBackground\tMean\tGreen\t%8.3f\t1/Mm\n",    $aBbsGbkg*1E6;
  printf "Back\tBackground\tMean\tRed\t%8.3f\t1/Mm\n",            $aBbsRbkg*1E6;
  printf "Total\tBackground\tStdDev\tBlue\t%8.3f\t1/Mm\n",  $sBtsBbkg*1E6;
  printf "Total\tBackground\tStdDev\tGreen\t%8.3f\t1/Mm\n", $sBtsGbkg*1E6;
  printf "Total\tBackground\tStdDev\tRed\t%8.3f\t1/Mm\n",   $sBtsRbkg*1E6;
  printf "Back\tBackground\tStdDev\tBlue\t%8.3f\t1/Mm\n",   $sBbsBbkg*1E6;
  printf "Back\tBackground\tStdDev\tGreen\t%8.3f\t1/Mm\n",  $sBbsGbkg*1E6;
  printf "Back\tBackground\tStdDev\tRed\t%8.3f\t1/Mm\n",    $sBbsRbkg*1E6;

exit 0;
```

(end of program)