

# **TSI Model 3563 Integrating Nephelometer Optical System Care**

**Recommended procedures and practices for evaluating,  
maintaining, optimizing, repairing and replacing components  
of the nephelometer optical system**

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## INTRODUCTION

The TSI Model 3563 Integrating Nephelometer measures light scattering by aerosols at three visible wavelengths and over two ranges of angular integration. By making frequent filtered-air background measurements to determine the Rayleigh and wall contributions to the total signal, the amount of light scattering by the aerosol particles is determined. The TSI Integrating Nephelometer was designed specifically for studies of direct radiative forcing of the Earth's climate by aerosol particles. They are still widely used in atmospheric monitoring networks for this purpose and to monitor air quality and visual range.

As TSI nephelometers age, degradation of the optical components occurs that decreases the detected photon intensity, which can lead to an extremely noisy signal. With some of these instruments approaching 25 or more years of age, it is important to address this issue to maintain reliable measurements. It is the purpose of this manual to provide guidance on how to properly maintain the nephelometer optical system and to replace components if/when that becomes necessary. This document is not meant to be a replacement for the TSI Model 3563 Integrating Nephelometer manual (hereafter referred to as the 'TSI nephelometer manual' posted at: [https://gml.noaa.gov/aftp/aerosol/doc/inst/neph/TSI\\_neph\\_manual\\_2009-10.pdf](https://gml.noaa.gov/aftp/aerosol/doc/inst/neph/TSI_neph_manual_2009-10.pdf)) which has much useful information on all aspects of care for the instrument, and relevant parts of that manual are referenced a number of times in this document. Instead, this report is intended to augment the descriptions in the TSI manual, providing helpful hints, best practices, descriptions of more complicated procedures not discussed in the TSI manual, etc., based on our years of experience with these instruments. It focuses solely on components of the optical system, from the lamp to the photomultiplier tube detectors, and it provides instructions on how to inspect, evaluate, clean, and/or replace the components to increase the photon count rates.

This document is provided as a service to the global nephelometer community. After almost 25 years of production, TSI stopped manufacturing the Model 3563 nephelometer in December 2016. This nephelometer is still widely regarded as one of the best, most sensitive, and most reliable instruments for measurement of the aerosol light scattering coefficient. Discussions with the TSI technical staff suggest that they will continue to support the maintenance, repair and calibration of these instruments going forward, at least until they run out of replacement parts. TSI has already had to change a number of components in the original design that have gone obsolete (e.g., zero filter valve, internal chopper and backscatter shutter motors, etc.). Some components of the optical system have also gone out of production and TSI has changed them without notifying customers. This document identifies those changes, and also provides vendors where possible, because soon it will not be possible to send a Model 3563 nephelometer to TSI and the user will have to repair the instrument.

## NEPHELOMETER OPTICAL SYSTEM

The following two-paragraph description of the optical path is from the TSI nephelometer manual (Ch.1, pg. 2)...

The light from a broadband halogen lamp is directed through an optical light pipe and opal glass diffuser to illuminate the internal scattering (sample) volume of the nephelometer. The sample volume is viewed by three photomultiplier tubes (PMTs) through a series of apertures set along the axis of the main instrument body. Aerosol scattering is viewed against the backdrop of a very efficient light trap. The light trap, apertures, and a highly light-absorbing coating on all internal surfaces of the instrument combine to give a very low scatter signal from the walls of the instrument.

Dichroic filters, in front of the PMTs, split and direct the light, which has been scattered by aerosol. The light is directed into three bandpass filters, blue, green and red. A constantly rotating reference chopper has separate areas to provide three types of signal detection. The first area gives a measure of the aerosol light-scattering signal allowed by an opening in the rotating chopper. The second area blocks all light from detection and gives a measurement of the PMT dark signal which is subtracted from the measurement signal. The third area is a translucent portion of the chopper, illuminated by the halogen lamp, which provides a measure of the light-source signal. In this way, over time, any change in the light source or in detector efficiency is compensated.

Fig. 1 shows a schematic of the Model 3563 Integrating Nephelometer, which shows the major elements of the nephelometer optical system. In this section, each component of the optical system is discussed, and guidance is provided on how to inspect, evaluate, clean, maintain, repair and/or replace system components. Some routine maintenance operations can be found in the TSI nephelometer manual. The instructions in this report are meant to augment the descriptions in the nephelometer manual, or to discuss procedures not covered there. There are many other maintenance documents available on our web site ([https://gml.noaa.gov/aero/maintenance/maint\\_info\\_docs.html](https://gml.noaa.gov/aero/maintenance/maint_info_docs.html)) for nephelometer care, maintenance and repairs, but this document focuses only on the optics.

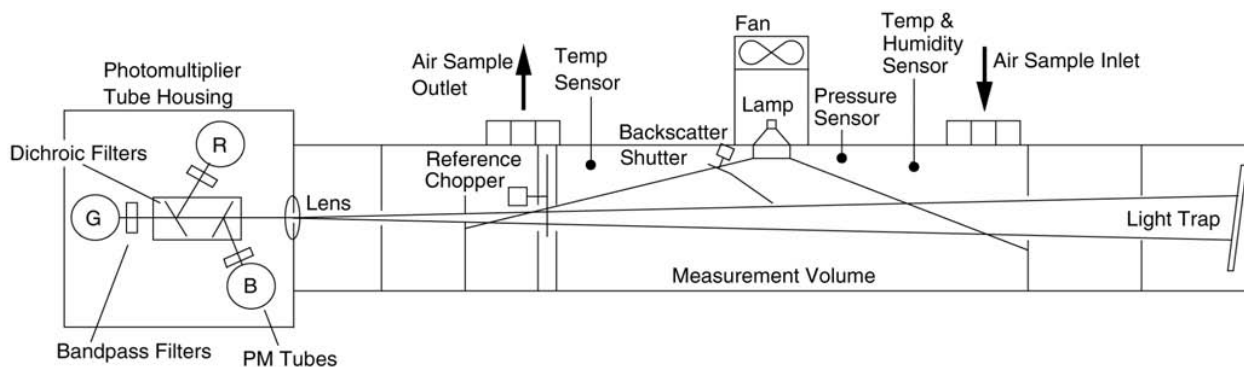


Fig. 1. Nephelometer schematic.

The optical path in the TSI nephelometer is shown below:

Lamp → light pipe assembly → chopper shutter → collimating lens → dichroic filters → color bandpass filters → photomultiplier tubes.

### Nephelometer lamp

The original nephelometer lamp was manufactured by GE. The lamp model was GE 20840 EYC Q71MR16/C/FL40. At some point TSI switched to a similar GE lamp with a cover glass; the model was GE 20873 EYC/CG Q71MR16C/CG40A (see Fig. 2). TSI provided no reason for this change; our guess is that the original halogen lamps either became difficult to procure or that the newer lamps with the cover glass provided a benefit (e.g., less heating of the light pipe or lower UV emission).



Fig. 2. Nephelometer lamp GE 20873 EYC/CG Q71MR16C/CG40A.

Unfortunately production of both of these lamps from GE has been discontinued. We recommend buying these now if you can find them, and we are currently in the process of finding a suitable replacement lamp. We will update this document when we find a viable lamp replacement.

As the filament ages the lamp begins to pull more current. Replacement of the lamp should occur when the current draw increases to  $> 6.5A$ . Allowing the lamp current to increase to higher levels is risky as it can lead to circuit board damage. For this reason, lamp current should be one of the routinely monitored parameters of the nephelometer. The simple procedure for replacing a nephelometer lamp is given in the TSI nephelometer manual in Ch. 8, pg. 11-12, and is not discussed further here.

### Light pipe assembly

The light pipe assembly passes light from the lamp into the nephelometer scattering volume. It consists of three parts: the lens, the light pipe, and the opal glass diffuser. The lens collects light from the lamp and focuses it onto the light pipe. The light pipe is a solid glass rod that transfers light from the lamp to the inside of the nephelometer, providing a thermal buffer between the lamp and the measurement volume. The opal glass diffuser is attached to the internal end of the light pipe with an optical adhesive. This adhesive has a refractive index between that of the light pipe and the opal glass to minimize light refraction at an interface of two different refractive indices.

The lens and the diffuser are at opposite ends of the light pipe and are exposed to air so over time they can become dirty. The light pipe lens (see Fig. 3), which receives a high volume of cooling air, may require frequent cleaning. A simple procedure for doing this is described in the TSI nephelometer manual (Ch. 8, pg. 16-18).

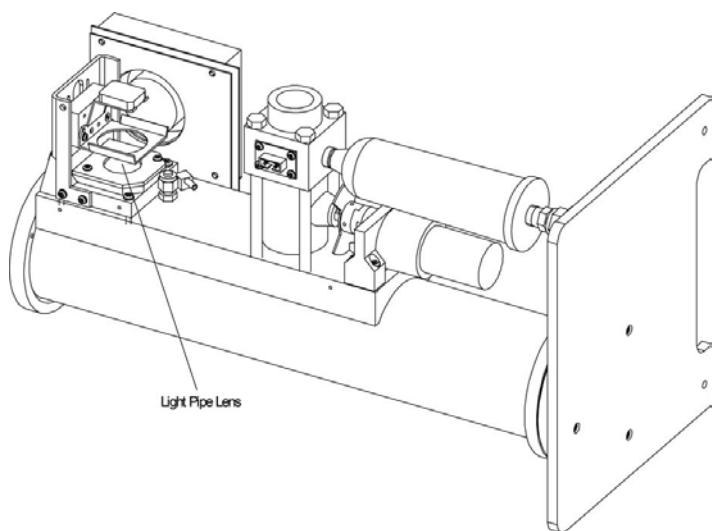


Fig. 3. Location of the light pipe lens.

The opal glass diffuser is exposed to the aerosols inside the nephelometer. Over time a layer of particulate material can accumulate on this diffuser which can reduce light transmission. The diffuser is shown in Fig. 4 (labeled 'Light Pipe Outlet'), and it is accessible in one of two ways. One method is to open the nephelometer by separating the two sections at the middle flange by removing the three flange screws and disconnecting all tubes and cables that connect the two sections. The other method is to remove the lamp base assembly, and this method is discussed in detail in the section below on light pipe replacement. A simple procedure for cleaning this diffuser is given in the TSI nephelometer manual in Ch. 8, pg. 26-34. While cleaning this diffuser, it is a good idea to also carefully wipe any dirt/dust off the backscatter shutter, taking care not to bend it.

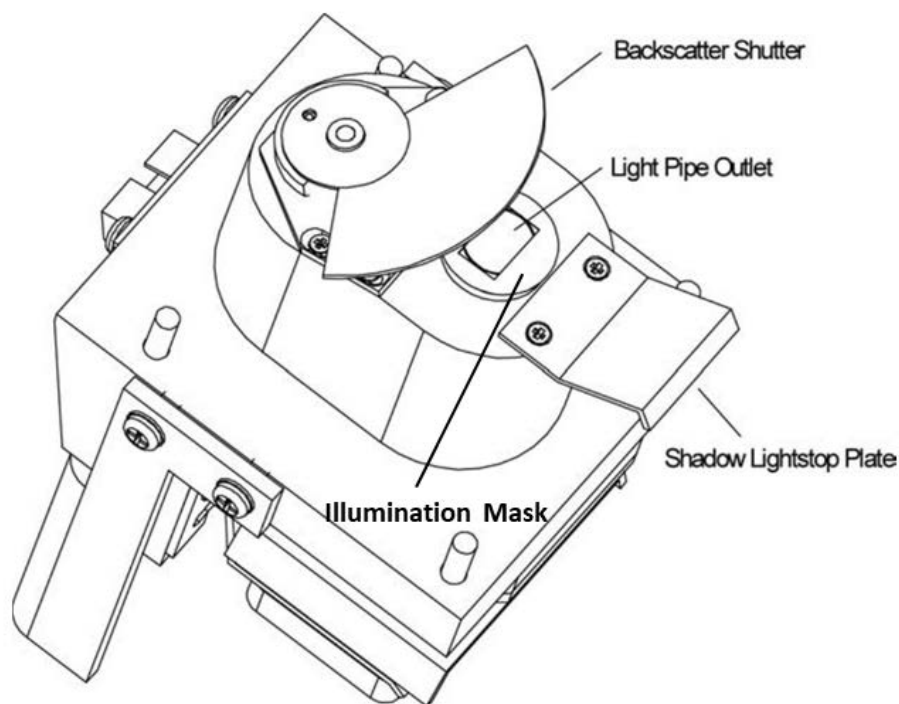


Fig. 4. The lamp base assembly viewed from below.

The light pipe is located directly under the light pipe lens, between the lens and the opal glass diffuser. Normally the light pipe itself should never need to be replaced. Over years of use, however, the heat from the halogen lamp causes the clear optical adhesive that bonds the opal glass diffuser to the light pipe to discolor and turn brown, which can significantly decrease the amount of light passing through the light pipe assembly into the nephelometer scattering volume.

The aging of the light pipe assembly disproportionately affects the blue photon counts more so than the green or red counts. When white light from the halogen lamp shines through this brownish layer, the light passing inside to the nephelometer measurement volume has an orange tinge to it. This is because of the preferential absorption of light by this layer at the shorter visible wavelengths (i.e., blue light), while the green through red part of the visible spectrum passes with less absorption. While all of the color channels will see lower counts because of light attenuation in a degraded light pipe, blue will be affected the most, followed by green, and red will show a smaller decrease in counts relative to a clear light pipe. Fig. 5 shows an example of scattering data from a nephelometer with a degraded light pipe assembly at one of the NOAA Baseline Observatories. It is evident that the blue signal is far noisier than either the green or red signals, and this is due to the extremely low blue photon count rates.

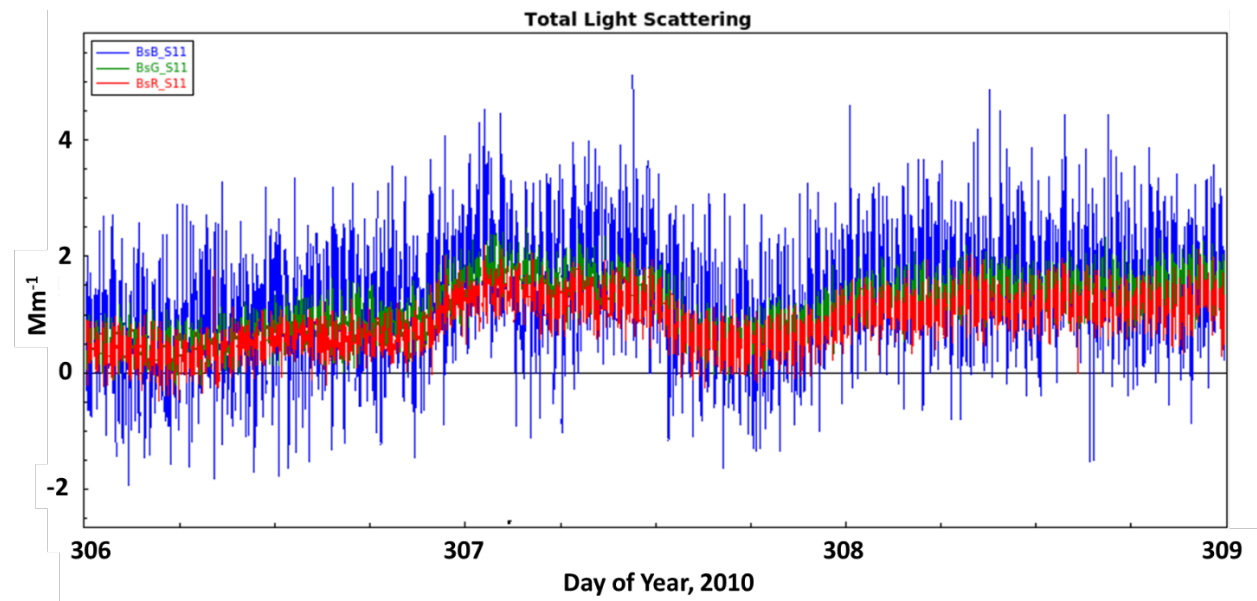


Figure 5. TSI Model 3563 nephelometer displaying a noisy blue scattering signal due to very low blue photon count rates at South Pole, Antarctica.

To confirm a degraded light pipe, one must either take apart the light pipe assembly and check for the brown deposit or check for the orange light emanating from the light pipe outlet. Neither of these procedures is particularly simple to do, but they can be accomplished by users with some technical ability or general experience in instrument maintenance and repair. They are described here as users may have to try this themselves because at some point the manufacturer will stop accepting instruments for repair. Anyone wishing to try these may wish to contact us and discuss the procedures. Note that other parts of the nephelometer optical system can cause a weak blue signal, including a degraded blue color bandpass filter or a weak blue PMT (see sections below for details). We recommend examining these other optical

components first for potential causes of the low blue photon counts before investigating the light pipe assembly because they are much easier to check.

The removal and repair of the light pipe assembly requires a Phillips screwdriver, a heat gun, the optical adhesive (Norland Optical Adhesive 61, <https://www.norlandprod.com/adhesives/noa%2061.html>), some white Teflon tape, and a UV lamp (used to cure the adhesive). Removing the light pipe from its housing beneath the lens involves removing the lamp base assembly from the nephelometer body to gain access to the bottom of the light pipe. The procedure to do this is described in the TSI nephelometer manual (Ch. 8, pg. 26-34; see Fig. 6). After removing the lamp base assembly from the nephelometer body, the light pipe lens must be removed (by backing out the two screws that hold it in place) from the assembly which exposes the top of the light pipe. The brass retaining ring beneath the lens must also be removed (unscrewed) which will allow the light pipe to move when pushed upward from the bottom (see Fig. 4). In order to better access the light pipe, first position the backscatter shutter out of the way so that it is rotated 180° from the orientation shown in Fig. 4. The light pipe must be pushed upward through its housing from the outlet side. Care must be taken when pushing on the opal glass diffuser because the rectangular mask is thin and fragile and can easily be damaged. We have found that pushing with a cotton swab works reasonably well if the light pipe is not stuck too tightly in its housing. After the light pipe is pushed upward by 10 cm or so the light pipe can be pulled out of the top of its housing by hand.

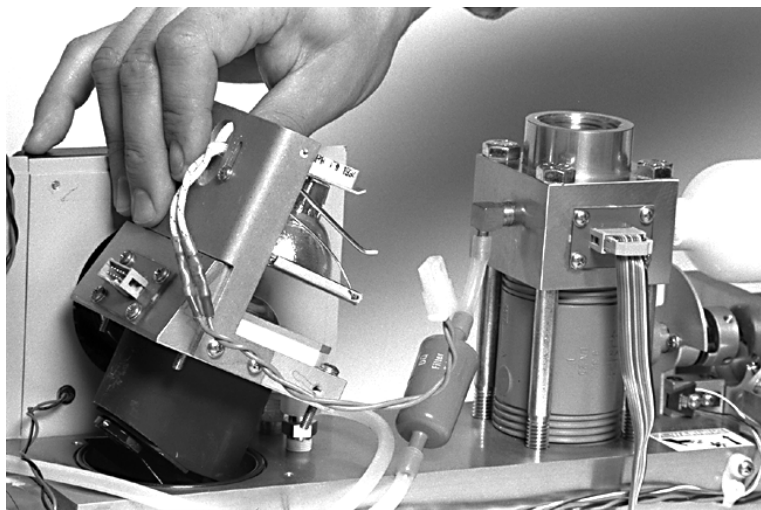


Fig. 6. Removing the lamp base assembly from the nephelometer body.

After the light pipe is free, the white Teflon ferrule and Teflon tape wrapping the glass should be removed so that the glass cylinder is completely visible. Fig. 7 shows an example of the



discolored adhesive bonding the opal glass diffuser to the cylindrical glass rod in a degraded light pipe assembly.

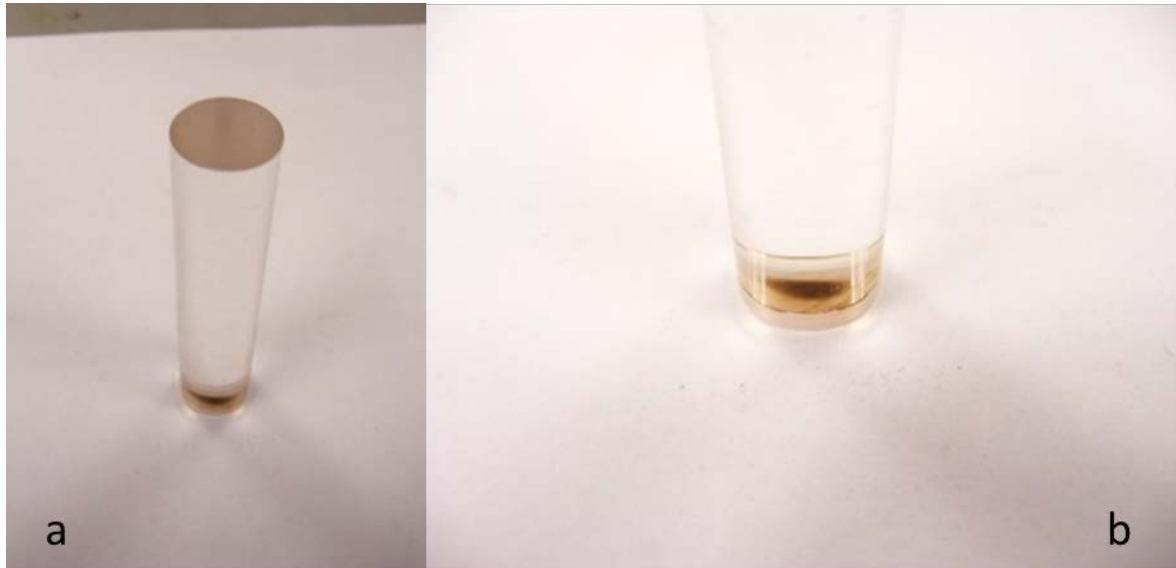


Fig. 7. The discolored optical adhesive between the glass light pipe rod and the opal glass diffuser. (a) full view of light pipe, (b) close up of discoloration.

In order to separate the light pipe from the opal glass diffuser, a heat gun is used to heat the opal glass diffuser to a high enough temperature to melt the adhesive. A variable-control heat gun works best so that the temperature can be gradually increased to get the adhesive to melt. General heat-resistant or welder's gloves can be used to hold the light pipe end farthest from the diffuser while the diffuser is being heated with the heat gun. The diffuser should be heated slowly to a high temperature, and after the opal glass diffuser releases, both light pipe and diffuser should be allowed to cool down very slowly. Rapid cooling of the light pipe can crack the glass. Setting the hot light pipe down on a warm tray or trivet will work, and a small fan can be used to cool the light pipe by circulating room air. Do not use any liquids (e.g., water, ethanol, etc.) to speed the cooling of a hot light pipe as this will almost certainly cause the light pipe glass to crack. The light pipe should be allowed to cool for 60 minutes or more at room temperature, or until it can be picked up by hand and not seem very warm to the touch.

After the light pipe and opal glass diffuser are separated and cool, acetone and a clean lab wipe can be used on both surfaces to remove the old brown adhesive. The wipe does not have to be a lens cloth, as minor abrasion makes the adhesive removal easier and tiny scratches imparted during the cleaning procedure will be filled in by the new adhesive. After the brown layer is removed from both surfaces, use a small amount of optical adhesive to attach the opal glass diffuser to the light pipe. The UV lamp is then used to cure the adhesive. The time required for

curing depends on the UV intensity... our high intensity UV lamp only takes 10-15 minutes for a full cure.

The glass light pipe tube should be wrapped in white Teflon tape as it was before the repair. Take care not to wrap too much tape around the glass cylinder or it will be difficult to slide back into the housing. Push the opal glass diffuser end of the light pipe down into the hole until it stops 1-2 mm short of the illumination mask. Be sure to insert the white Teflon ferrule back onto the light pipe. Then replace the brass ring and turn it to compress the ferrules, which will move the light pipe downward so that the opal glass diffuser just touches the illumination mask. If the brass ring is loose when the diffuser touches the mask you may have to start this insertion process again and re-position the ferrules so that when the brass ring is tight, the opal glass diffuser is just touching the illumination mask. Then the lamp base assembly can be re-installed onto the neph body. Lubrication of the o-ring on the neph body is a good idea when performing this repair.

If it is preferable to confirm a degraded light pipe assembly by inspecting whether the light emanating from the light pipe outlet has an orange tinge to it, this procedure can be accomplished by opening the nephelometer body in a darkened room. The nephelometer should be positioned horizontally on a large table, and power should be turned off and the power cord disconnected from the instrument. The nephelometer should be opened along the middle flange, as shown in Fig. 8. In this image, the chopper shutter assembly is just inside of the left hand side of the nephelometer, and the lamp base assembly, containing the light pipe outlet and backscatter shutter, is inside the right side.

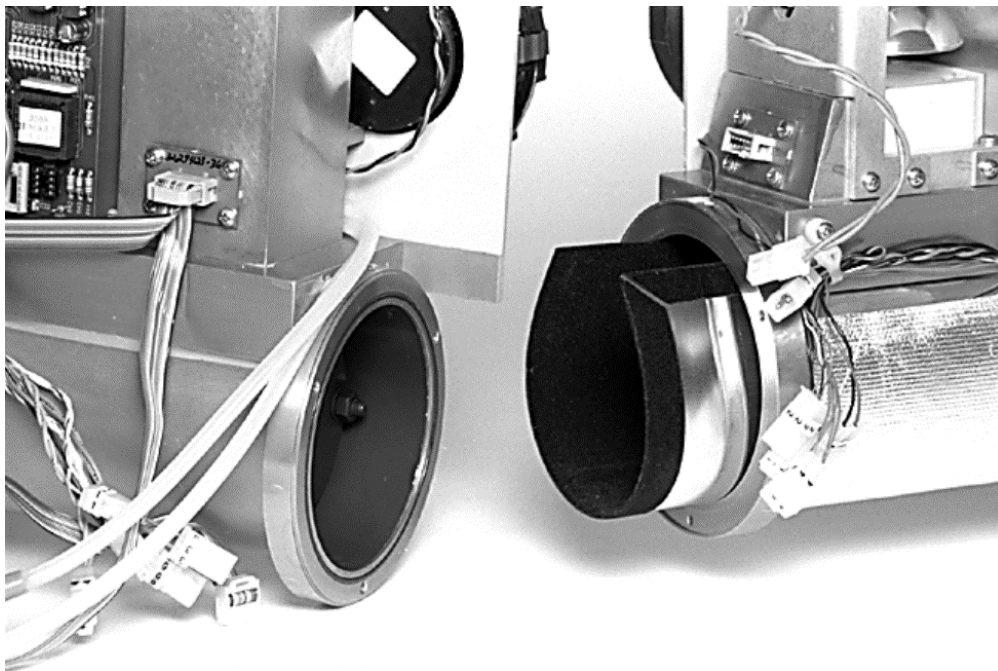


Fig. 8. Nephelometer split at the midpoint flange.

Whenever the PMTs are able to sense room light, power should not be applied to the instrument as that will damage the PMTs. Since this procedure requires the lamp to illuminate, however, power will be required. A recommended way to prevent damage to the PMTs is to a) reduce room lighting to the minimum necessary to perform the procedure, and b) place a piece of black electrical tape over the round aperture in the chopper shutter assembly to block light from the room or lamp from reaching the PMTs.

In Fig. 8, the electrical connections between the two halves of the nephelometer have been broken. These will need to be re-connected before the lamp will illuminate. You may have to move the two halves of the nephelometer closer together than shown in this figure in order for the electrical cables to reach each other. The black flocked paper insert can be removed if necessary. After the cables have been reconnected, power can be applied to the instrument. The lamp should then illuminate. If the light coming from the light pipe outlet has a slight orange color to it rather than bright white, then the optical adhesive in the light pipe assembly has discolored and the light pipe should then be repaired to achieve an acceptable blue signal.

#### Reference chopper shutter

The reference chopper shutter is a disk that is turned at roughly 23 revolutions per second by one of the internal motors and rotates in the nephelometer optical path. A drawing of the chopper shutter is shown in Fig. 9. The chopper shutter provides three measurements per revolution. The signal section simply allows light to pass through unaltered and provides a measurement of the light scattered within the nephelometer measurement volume. The dark section is opaque and blocks all light from passing through, which provides a measurement of the photomultiplier tube (PMT) background noise. The third section is a translucent calibrator, which is meant to be a stable, fixed-brightness object. The light source directly illuminates this section providing a measure of lamp stability over time. To reduce the lamp intensity to a level that will not saturate the photomultiplier tubes, the calibrate section incorporates a neutral density filter that blocks approximately 99.9% of the incident light.

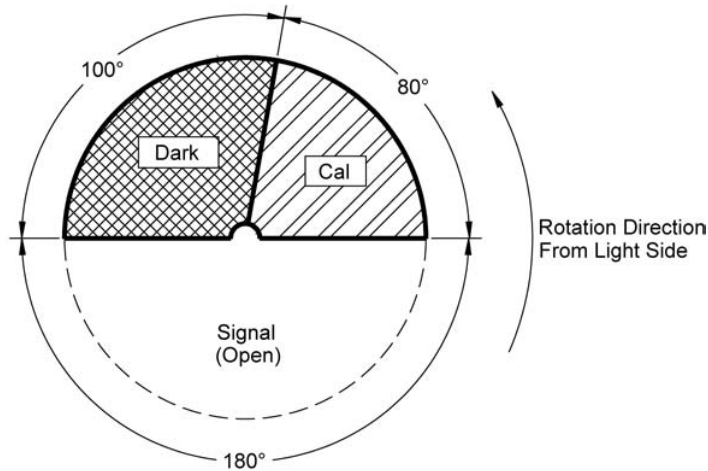


Fig. 9. Reference chopper shutter showing signal, dark and calibrator sections.

With continued use, particulate material can deposit and build up on the chopper shutter. This is especially important for the calibrator section because an accumulating aerosol deposit on the calibrator section can gradually change the amount of light that is transmitted to the PMTs. Thus, for a constant amount of aerosol scattering, the detected signal will decrease over time if the calibrator is becoming increasingly dirty. This results in calibration drift and errors in the scattering measurement. The procedure for cleaning the reference chopper shutter with isopropyl alcohol and a lens cloth or cotton swab is given in the TSI nephelometer manual Ch. 8, pg. 19-25. Only very light pressure should be applied to the calibrator section to remove dust/dirt. Care should be taken so as not to scratch the coating. A document we have put together for removal of the chopper shutter assembly can be found at [https://gml.noaa.gov/aero/maintenance/Neph Removal of TSI Neph chopper motor assembly.pdf](https://gml.noaa.gov/aero/maintenance/Neph%20Removal%20of%20TSI%20Neph%20chopper%20motor%20assembly.pdf) and instructions for replacing the chopper motor are here: [https://gml.noaa.gov/aero/maintenance/Neph chopper motor repair.pdf](https://gml.noaa.gov/aero/maintenance/Neph%20chopper%20motor%20repair.pdf)

### Backscatter shutter

Instructions are here:

[https://gml.noaa.gov/aero/maintenance/Neph\\_backscatter\\_shutter\\_repair.pdf](https://gml.noaa.gov/aero/maintenance/Neph_backscatter_shutter_repair.pdf)

Specifications for positioning are here:

[https://gml.noaa.gov/aero/maintenance/Neph\\_backscatter\\_shutter\\_specs.pdf](https://gml.noaa.gov/aero/maintenance/Neph_backscatter_shutter_specs.pdf)

### Collimating lens

The collimating lens (see Fig. 1) separates and seals the nephelometer volume from the PMT housing and provides the channel for scattered light to get to the PMTs. It collimates light from apertures that define the viewing volume in the body of the instrument. The light is collimated before it is split into separate colors to ensure that each photomultiplier tube sees the same area of light scatter from the viewing volume. Note that under normal circumstances, you do not have to periodically check or clean the lens. Check the lens if there are low counts in all three wavelengths, or if there is an overall reduction in the signals in over time. The procedure for cleaning the collimating lens is given in the TSI nephelometer manual in Ch. 8., pg. 47-49.

### Dichroic filters

Light passing through the collimating lens is directed onto the two dichroic filters (see Fig. 1), which reflect and transmit portions of the collimated light beam into the color bandpass filters. Note that with normal use the dichroic filters do not have to be cleaned. Check these filters if there is an overall reduction in the signal in one wavelength over time that cannot be explained by a degraded color bandpass filter or an aging PMT. Cleaning can be performed with isopropyl alcohol and a cotton swab. Care must be taken not to scratch the surface of or change the alignment of the dichroic filters.

### Color bandpass filters

The color bandpass filters (see Fig. 1) are positioned at the light input to each PMT and only allow photons of a limited wavelength range to pass through. The three bandpass filters are centered at 450 nm (blue), 550 nm (green), and 700 nm (red) wavelengths. Although located within a protective can (the PMT housing), the filters may need periodic cleaning if they accumulate dust or dirt. In addition, exposure to high humidity can attack the coatings on the filters causing them to cloud and thus decrease the photon counts. A procedure is given in the TSI nephelometer manual for removal of the filters for checking, cleaning or replacing the bandpass filters (see Ch. 8., pg. 43-47).

The degradation of these bandpass filters over time is a well-known phenomenon, and eventually all nephelometers will need to have their color filters replaced. Unfortunately, the original filters supplied with the nephelometers are no longer available. TSI originally used Corion color bandpass filters (see the red cells in Table 1). These filters went out of production and became unavailable in about 2015. TSI then switched to the Newport replacement filters which are still available from TSI and from the manufacturer (yellow cells in Table 1). Note that the replacement color bandpass filters from Newport have the same form factor (1.00-inch diameter, 0.25-inch thickness) as the Corion filters, which is probably why TSI went with this replacement option. They do have somewhat higher peak transmittances than the original

filters, but they also have a much larger full width half maximum (FWHM) value (70nm vs. 35-40nm for the Corion filters). We have researched other color filters and have found another replacement option. These are color bandpass filters made by Intor, Inc. (<https://www.intorfilters.com/>). The specifications for these filters are shown in the orange cells in Table 1, and the part numbers include links to the Intor spec sheets. The tolerance of the center wavelength is actually a bit better than the original Corion color filters, the peak transmittance is higher, and the FWHM values are slightly narrower. These appear to be a better replacement option for the original Corion filters, and they are less expensive also (<\$100 per filter as of this writing (Apr. 2020)). The only problem is that the form factor is slightly different; the Intor color filters are not quite as thick as the other filters. To account for this we use an x-profile o-ring (McMaster-Carr Part # [90025K362](#)) as a spacer in the filter holder as shown in Fig. 10. A small Phillips screwdriver is used to secure the color bandpass filter in its holder as shown in Fig. 11. The screw should only be hand-tightened to avoid damage to the rim of the color filter.

Table 1. Specifications of the color filters used in TSI Model 3563 nephelometers.

<u>TSI Part #</u>	<u>Nominal Wavelength</u>	<u>Manufacturer</u>	<u>MFG Part #</u>	<u>Vendor</u>	<u>Center <math>\lambda</math> &amp; Tol (nm)</u>	<u>Peak Trans &amp; Tol (%)</u>	<u>FWHM &amp; Tol (nm)</u>
2502486	450nm	Corion	S40-450-F	Newport-Franklin	450 $\pm$ 8	45%	35 $\pm$ 8
2502486	450nm	Newport	10BPF70-450	Newport-Franklin	450 $\pm$ 10	60%	70 $\pm$ 30
n/a	450nm	Intor	<a href="#">450-40-60</a>	Intor	450 $\pm$ 5	60%	40 $\pm$ 5
2502485	550nm	Corion	S40-550-F	Newport-Franklin	550 $\pm$ 10	50%	40 $\pm$ 8
2502485	550nm	Newport	10BPF70-550	Newport-Franklin	550 $\pm$ 10	60%	70 $\pm$ 30
n/a	550nm	Intor	<a href="#">550-40-75</a>	Intor	550 $\pm$ 5	75%	40 $\pm$ 5
2502487	700nm	Corion	S40-700-F	Newport-Franklin	700 $\pm$ 6	50%	40 $\pm$ 8
2502487	700nm	Newport	10BPF70-700	Newport-Franklin	700 $\pm$ 10	60%	70 $\pm$ 30
n/a	700nm	Intor	<a href="#">700-40-75</a>	Intor	700 $\pm$ 5	75%	40 $\pm$ 5

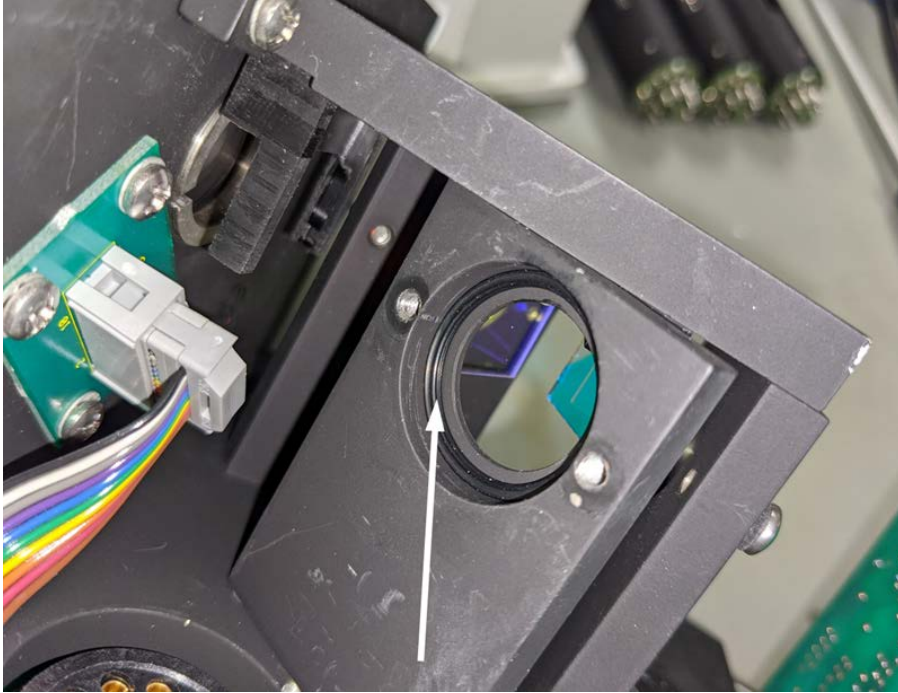


Fig. 10. The x-profile o-ring used as a spacer for Intor filters in the color filter holder.



Fig. 11. Securing the color bandpass filter using a small Phillips screwdriver.

## Photomultiplier tubes

The photomultiplier tubes serve as the photon detectors in the TSI Model 3563 Integrating Nephelometer. A detailed discussion of the nephelometer theory of operation is available in Chapter 7 of the TSI nephelometer manual which shows all of the calculations used to convert the raw signals from the PMTs into scattering coefficients. The manual goes into considerable detail describing 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. This section of this document is meant 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. For diagnostic purposes, it is preferable to have the nephelometer filled with filtered air so the variability due to particles is eliminated.

Recall that Fig. 9 shows a schematic drawing of the reference chopper. 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 PMTs. The calibrator is supposed to be a 'fixed-brightness object', which can be used to relate a measured amount of photon counts to a known amount of light scattering (as is done in a calibration). Unfortunately, the calibrator brightness is not truly fixed. Its brightness changes over time due to particle deposition and aging of the optical coating, 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, as can photons scattered from the wall. These non-aerosol contributors to the signal counts can lead to noisy signals, and highlight the importance of keeping the interior of the nephelometer clean and the walls black. 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 is shown in Table 2. These data were acquired using a typical NOAA nephelometer during a measurement of filtered air.

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' (TS) channels, which contain the photon counts recorded when the backscatter shutter is out of the optical path. 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 BLUE $\geq$ 80,000 Hz,



GREEN $\geq$ 100,000 Hz and RED $\geq$ 100,000 Hz for the TS-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 can lead to higher variability in gas calibration checks, and in order to minimize this we try to maximize the TS-CAL photon count rates. In the example above, all of the TS-CAL count rates are considered acceptable.

Table 2. Typical NOAA Nephelometer Photon Count Frequency (Hz) on Particle-free Air.

Color	Total Scatter			Backscatter		
	Calibrate	Signal	Dark	Calibrate	Signal	Dark
Blue	82562	740	8	43865	375	6
Green	125731	814	5	87028	501	3
Red	140689	936	278	110645	711	245

If one or more of the color channels shows photon counts significantly below the acceptable target values in Table 2, then the user should investigate the cause of the problem. This is generally done by process of elimination, understanding that more than one issue could contribute to low photon counts. If all color channels show low TS-CAL count rates, the problem may be an aging or weak lamp, a degraded light pipe, a dirty chopper shutter, or a dirty collimating lens. It is also possible, however, that all of the color filters could be aged and hazy or that all of the PMTs could be old and weak.

The first and easiest thing to check when all color channels show low counts is the nephelometer lamp. The lamp can be replaced with a new one and the count rates observed to see if they have increased. If they have not, then the new lamp did not solve the problem and you might as well re-insert the old lamp into the lamp housing. The next things to check, in order of increasing difficulty, would be the collimating lens and the reference chopper shutter. Both of these can be cleaned relatively easily, and if a heavy particulate deposit is removed, the count rates should increase significantly.

If the photon count rates do not increase to acceptable levels, the other potential problems should be investigated, although these typically do not simultaneously affect all of the color channels. With no power to the nephelometer (and, just to be sure, disconnect the power cord!), the PMT housing 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. Fig. 12a shows the position of a PMT observed after shipping and Fig. 12b after it has been re-seated into its socket

properly. The PMT in Fig. 12(a) will count lower than the properly-seated PMT in Fig. 12(b). Re-seat the PMTs by wiggling them and pressing them downward into their sockets, and then replace the PMT housing cover. Only after the cover has been secured by tightening the four screws should power be applied to the instrument. Applying the high voltage to the PMTs in room light with the PMT housing cover completely or partially removed will result in permanently damaged PMTs.

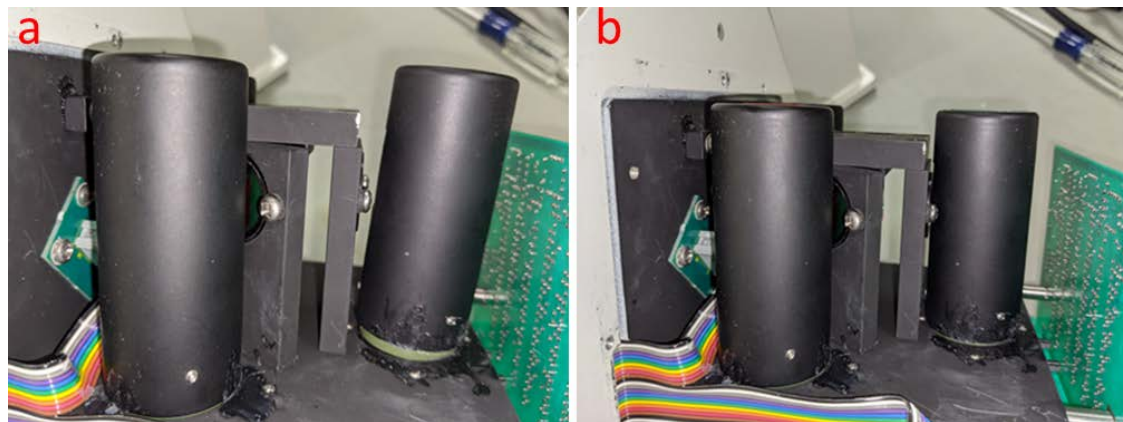


Fig. 12. (a) Improper position of green PMT after shipping. (b) Proper position of green PMT after re-seating into its socket.

Another problem that can happen if the PMTs have been replaced before or if the PMT's magnetic shield slips relative to the PMT is misalignment of the tube with the shield window. The PMT should be pushed all the way up into its shield, so that it contacts the rubber stop at the top of the shield, and the PMT detection screen should be centered between each side of the shield opening before tightening the three 0.050" allen set screws to secure the PMT. A procedure for replacing PMTs is provided in the TSI nephelometer manual in Ch. 8, pg. 41-43. Fig. 13 shows both (a) a red PMT that is not properly aligned with its magnetic shield window, and (b) a properly aligned red PMT inside its shield. The PMT shown in Fig. 13(a) will count significantly lower than the PMT in Fig. 13(b).

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.

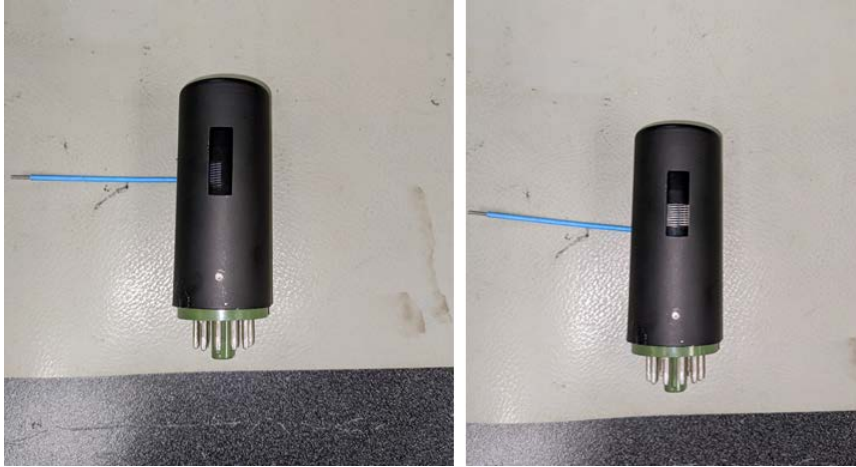


Fig. 13 (a) A poorly-aligned red PMT. (b) A properly-aligned red PMT.

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 or sampling filtered air. 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 CAL and SIGNAL photon counts will not increase much with increasing voltage. At this point the PMT count rate has plateaued, and operation can either commence at this voltage or the voltage can 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 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 PMTs used in the TSI nephelometer are produced by Hamamatsu, Inc., and can be ordered directly from the Hamamatsu web site ([https://www.hamamatsu.com/us/en/product/optical-sensors/pmt/pmt\\_tube-alone/side-on-type/index.html](https://www.hamamatsu.com/us/en/product/optical-sensors/pmt/pmt_tube-alone/side-on-type/index.html)). Note that this is the US web portal and international customers should switch to the portal appropriate for their region or country. The PMT used in the blue and green channels is Part #R1527P, while the PMT used in the red channel is Part #R2949. At the time of this writing (Apr. 2020) TSI still had limited stock of these PMTs.

The BLUE $\geq$ 80,000 Hz, GREEN $\geq$ 100,000 Hz and RED $\geq$ 100,000 Hz values 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 shown in Fig. 5, the noise in the blue signal is much larger than the noise in either the green or red signals. This is because of the extremely low blue photon count rates (TS-CAL (BLUE) photon count rate  $\approx$  25 kHz) due to blue wavelength light being preferentially absorbed by the discolored adhesive in the light pipe. In

this example, a count rate of TS-CAL (GREEN)  $\approx$  90KHz did not show an overly noisy signal, but in some cases the noise can be larger so it bears watching when below 100KHz.

The TS-SIGNAL photon counts depend not only on the other factors listed above, but also on air density. The TS-SIGNAL counts will then vary with elevation above sea level due to the relationship of Rayleigh scattering with air density. 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 ( $<$   $\sim$  30 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. Again, these are minimum targets and it is better to have SIGNAL – DARK photon counts of more than 400 Hz if possible. TS-SIGNAL – TS DARK count rates of  $>$  1000 Hz are great if you can get them but often this is not possible.

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 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 and cleaning the internal surfaces.

## **NEPHELOMETER CLEANING**

Strictly speaking the interior surfaces of the nephelometer are not part of the optical system. In fact, they are intended to be invisible to the detectors. The light trap, apertures, and a highly light-absorbing coating on all internal surfaces of the nephelometer combine to give a very low scatter signal from the walls of the instrument. When the nephelometer interior gets dirty, however, light scattering from these surfaces increases and the background values increase. This results in the subtraction of a larger ‘Rayleigh + wall’ signal from the total scattering signal to get aerosol light scattering, and this can have a significant influence on instrument noise, especially in cleaner environments. Since the condition of the nephelometer interior can affect optical system diagnostic measurements, we have chosen to discuss nephelometer cleaning in this document on optical system performance.

As discussed above, keeping the interior of the nephelometer clean is important for maximizing the aerosol signal above the background signals. Most of the interior surfaces have a black anodized coating to minimize light scattering from the walls. Over time, however, the interior can become dirty, leading to an increase in wall-scattered light. It is especially important to monitor this in dusty regions or coastal locations, as the dust and sea salt will coat the originally black interior with a white or light-colored deposit. It is also important to note that if the interior of the nephelometer becomes wet, the interior surfaces will reflect much more light. In this section we provide some tips on cleaning the nephelometer. This is also discussed in several places in Ch. 8 of the TSI nephelometer manual.

In general, routine cleaning of the nephelometer can be limited to the inlet section (i.e., the portion of the nephelometer containing the lamp with the nephelometer split at the mid-point flange). Typically, the only portion of the outlet section that requires occasional cleaning is the reference chopper shutter, and this procedure was discussed previously.

#### Cleaning of the flocked paper

The flocked paper insert is a sheet of aluminum covered with black felt that lines the measurement volume of the nephelometer. This very black, rough surface is meant to minimize scattering of photons back into the active scattering volume. The flocked paper is often the first place to get dirty in the nephelometer, and it is a primary contributor to the wall signal. A very detailed procedure for cleaning the flocked paper is provided in the TSI nephelometer manual in Ch. 8., pg. 34-39. The flocked paper should be checked annually and cleaned whenever the background signals increase over time.

#### Cleaning of the light trap

The light trap is in theory designed to capture all light entering it. The light trap mirror is positioned at an angle to reflect incident light into a black felt pad. It is very important to keep the light trap clean as the light trap mirror is directly in the optical path. This is especially true if the nephelometer is operated in the vertical position, as large particles (e.g., dust, soil, sea salt, etc.), fibers, or insects can settle on the mirror and cause a large increase in the background signals. This situation is most easily checked by routine monitoring of the nephelometer background scattering signals (available in the nephelometer 'Z' data records) on filtered air over time. Fig. 14 shows a dirty light trap mirror. The light-colored pieces of dust and dirt contribute to a larger background signal.

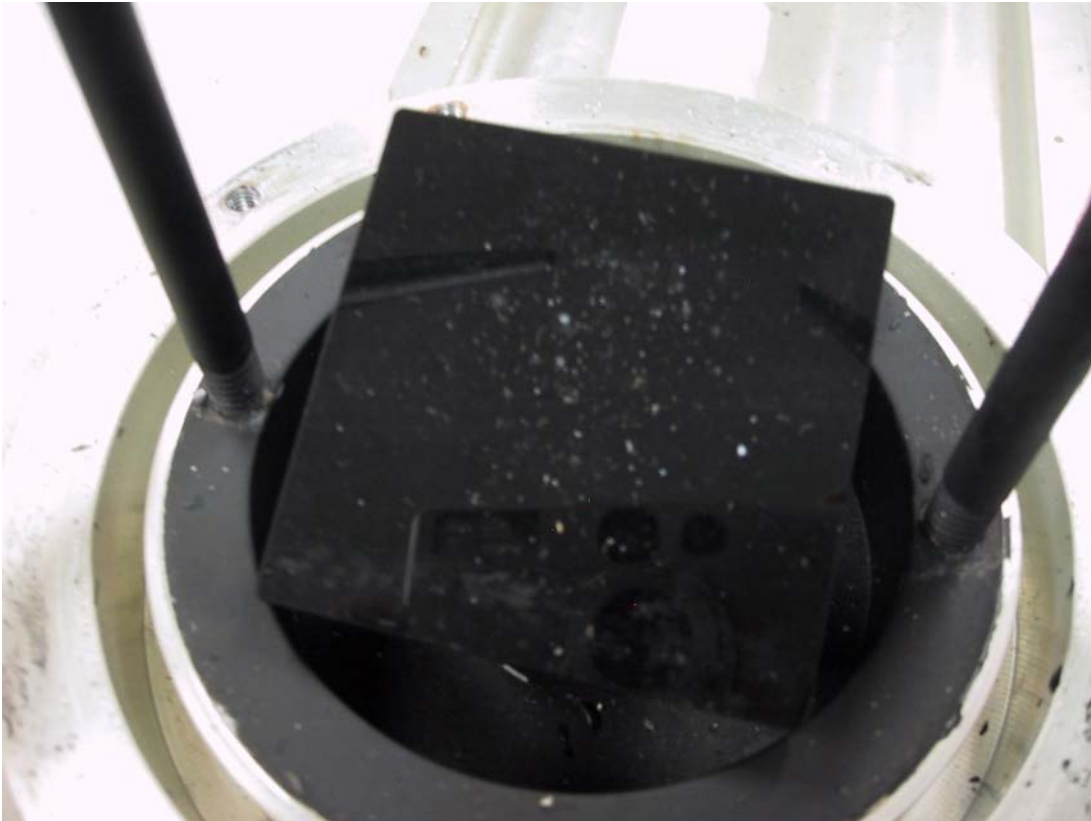


Fig. 14. A dirty light trap mirror.

A procedure for cleaning the light trap is not provided in the TSI nephelometer manual, so we have included it here. Fig. 15 shows the bottom flange of the nephelometer, which must be separated from the nephelometer tube in order to gain access to the light trap. The three flange screws (a) must be removed, and the nylon nut (b) must be unscrewed. Then the flange, which is attached to the light trap column, can be pulled away from the nephelometer tube.

Fig. 16 shows the light trap column. It can be opened by loosening and removing the two nuts at the top of the column. The pieces of the light trap column can be removed by sliding each piece up and off of the two threaded posts. These should be laid out carefully on the tabletop in the order and orientation they were removed so that they can be re-assembled in the proper order. The bottom section(s) contain black felt to trap photons reflected from the mirror and they must be replaced facing the mirror. Note that the nephelometer will not work properly if the order of the orifices inside this column has changed! After removal of the column, the light trap mirror should be visible (Fig. 14). Cleaning of the light trap mirror can be accomplished using a clean wipe or lens cloth along with ethanol or isopropanol, being careful not to scratch or leave a residue on the mirror. Re-assemble the light trap column as it was before, insert it into the nephelometer tube, and re-tighten the nylon nut and flange screws. When re-

connecting the inlet and outlet sections of the nephelometer, make sure the o-ring on the nephelometer bottom flange remains in the groove during this operation.



Fig. 15. Removal of the bottom flange for access to the light trap.



Fig. 16. The nephelometer light trap column.

### Cleaning of the apertures

The apertures in the light trap and chopper shutter columns define the scattering viewing volume, so the edges of these apertures and the areas immediately surrounding them are by definition visible to the detectors. Fig. 17 shows a close-up view of the first aperture in the light trap column. When cleaning of the nephelometer interior surfaces is performed, users should always inspect the apertures to make sure particles, fibers, cobwebs, spider webs, etc., are not clinging to the edges. These objects can reflect a large amount of light (relative to aerosols or gases in the scattering volume) back to the detectors and cause a large increase in the wall scatter values. When cleaning the apertures, use a clean lint-free cloth and alcohol, and re-inspect each aperture after cleaning to make sure fibers from the clean wipe did not deposit on the edge of the aperture. Shining a bright light on each aperture can help to spot tiny fibers. Using a cotton swab is not recommended as the cotton fibers often get stuck on the edge of the apertures.





Fig. 17. The first aperture in the light trap column.

## SUMMARY

Information and procedures have been provided to help users investigate, clean, maintain, troubleshoot and repair components in the optical system of the TSI Model 3563 Integrating Nephelometer. This document should be used alongside the TSI Model 3563 Integrating Nephelometer manual as much useful information is provided there.

Please feel free to contact us if you have questions about the information presented here. We can be reached at:

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