TSI Model 3563 Integrating Nephelometer Operations Reference Manual

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

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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 advising users of ways to optimize nephelometer performance, to recognize instrument problems, and 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. Most of the common preventative maintenance procedures are discussed in detail in the Instruction Manual that comes with 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.

Operations

<u>Arrival of New Instrument from Factory</u>

Initial Inspection

A Model 3563 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 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 before connecting the power cord to the nephelometer.*** ***<u>Applying power to the photomultiplier tubes with the PMT housing removed may permanently damage the PMTs</u>.***

- 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.

Performance Checks

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. There are two performance checks that can be done upon receipt of a new nephelometer. The first is 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. A span 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 checks that show large negative values are often caused by CO_2 either not entering the nephelometer as expected or not staying inside the instrument. 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 heap 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.

The second performance check is an instrument noise check. 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 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 (at least 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):	2-8	0.02-0.12
Neph. Background, Backward Scatter (all wavelengths):	1-9	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.

Arrival of Working Instrument

Same initial inspection and performance checks as for new instrument arrival, except that some additional maintenance and recalibration may be required. Refer to the Instruction Manual for calibration instructions. For possible maintenance required, see Routine Maintenance and Special Maintenance sections.

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.

- 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.

Calibrations

Detailed instructions on how to calibrate the nephelometer are given in Chapter Four 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 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 thickness or on the presence of scratches in the finish of the reflective coating on 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 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.

Diagnostic Measurements

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)
- 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 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.

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. 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)
- Calibration or replacement of the T, P, and RH sensors (check annually)

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
- Replacement of old/scratched chopper shutter
- Replacement of EPROM chip
- Replacement of motor control microprocessor
- 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

We recommend replacement of an old chopper shutter, rather than cleaning. We have found through experience that it is very difficult to clean one of these shutters without leaving a dull deposit or imparting additional scratches on the reflective surface. The TSI Nephelometer Instruction Manual recommends cleaning a dirty chopper shutter with isopropyl alcohol and cotton swabs. Feel free to try this, but don't be surprised if you end up needing a new chopper shutter anyway.

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. 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 lets ambient air into the instrument during the zero air background measurement, which obviously compromises the background measurement. This 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 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. They 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.

Repairs

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 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.

<u>NOAA Modifications</u>

We make several modifications to the standard TSI nephelometer. These include:

- installing plastic clips to hold the circuit boards together
- 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
- 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

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 CO_2 Rayleigh scattering at STP, as measured by nephelometer:

$$\mathrm{BSGCO2}[\lambda] = \mathrm{BSPCO2}[\lambda] / \mathrm{DENCO2} - \mathrm{BSPAIR}[\lambda] / \mathrm{DENAIR} + \mathrm{BSGAIR}[\lambda]$$

$$\mathrm{BBSGCO2}[\lambda] = \mathrm{BBSPCO2}[\lambda] / \mathrm{DENCO2} - \mathrm{BBSPAIR}[\lambda] / \mathrm{DENAIR} + \mathrm{BSGAIR}[\lambda]/2$$

Calculate percentage error in measured CO_2 Rayleigh scattering:

$$\mathrm{ERRTS}[\lambda] = (\mathrm{BSGCO2}[\lambda] / \mathrm{BSGCO2TRUE}[\lambda] - 1) * 100$$

$$\mathrm{ERRBS}[\lambda] = (\mathrm{BBSGCO2}[\lambda] / \mathrm{BBSGCO2TRUE}[\lambda] - 1) * 100$$

Calculate nephelometer sensitivity factor, defined as the photon count rate (Hz) attributable to Rayleigh scattering by air at STP:

$$\begin{aligned}\mathrm{SENSTS}[\lambda] = {} & (\, (\mathrm{HZTMEASCO2}[\lambda] - \mathrm{HZTDARKCO2}[\lambda]) / \mathrm{DENCO2} \\ & - (\mathrm{HZTMEASAIR}[\lambda] - \mathrm{HZTDARKAIR}[\lambda]) / \mathrm{DENAIR}\,) \\ & / (\mathrm{RAYCO2} - 1)\end{aligned}$$

$$\begin{aligned}\mathrm{SENSBS}[\lambda] = {} & (\, (\mathrm{HZBMEASCO2}[\lambda] - \mathrm{HZBDARKCO2}[\lambda]) / \mathrm{DENCO2} \\ & - (\mathrm{HZBMEASAIR}[\lambda] - \mathrm{HZBDARKAIR}[\lambda]) / \mathrm{DENAIR}\,) \\ & / (\mathrm{RAYCO2} - 1)\end{aligned}$$

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)