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Nephelometer Aboard Aircraft Instrument Handbook

J Uin L Goldberger

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ARM

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J Uin, Brookhaven National Laboratory
L Goldberger, Pacific Northwest National Laboratory

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Acronyms and Abbreviations

AAF	ARM Aerial Facility
ACE-ENA	Aerosol and Cloud Experiments in the Eastern North Atlantic
ARM	Atmospheric Radiation Measurement
ASCII	American Standard Code for Information Interchange
G-1	Gulfstream 159
HEPA	high-efficiency particulate air
Netcdf	Network Common Data Form
PMT	photomultiplier tube
RH	relative humidity
UTC	Coordinated Universal Time

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1.0 Instrument Title

The TSI model 3563 integrating nephelometer instrument is pictured in section 4.0, and more information can be found on the manufacturer's website. This model was used on the Gulfstream-159 (G-1) aircraft operated by the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Aerial Facility (AAF) up until 2019. The same instrument will be deployed on the new aircraft that will replace the G-1.

2.0 Mentor Contact Information

Mikhail Pekour
PO Box 999
Pacific Northwest National Laboratory
Richland, Washington 99352
Email: mikhail.pekour@pnnl.gov

3.0 Vendor/Developer Contact Information

TSI Incorporated
500 Cardigan Road
Shoreview, Minnesota 55126
FAX: +1 (651) 490-3824
Email: particle@tsi.com

4.0 Instrument Description

The integrating nephelometer (Figure 1) is an instrument that measures aerosol light scattering. It measures aerosol optical scattering coefficients by detecting (with a wide angular integration – from 7 to 170°) the light scattered by the aerosol and subtracting the light scattered by the carrier gas, the instrument walls, and the background noise in the detector (zeroing). Zeroing is performed during preflight for each research flight during a campaign. The test air volume is illuminated by a broad-spectrum light (halogen lamp); the scattered light is filtered into red (700 nm), green (550 nm), and blue (450 nm) channels and captured by three photomultiplier tubes. The instrument can measure total scatter as well as backscatter (from 90 to 170°; Heintzenberg and Charlson 1996, Anderson et al. 1996, Anderson and Ogren 1998, TSI 3563 2015).

On board the aircraft, the nephelometer samples directly from the isokinetic manifold with a designated heater mounted just upstream of the nephelometer inlet fitting. The internal relative humidity is controlled via temperature variation, and it is normally kept at or below 40%.

Figure 1. The TSI model 3563 integrating nephelometer. Image adapted from the manufacturer's website.

5.0 Measurements Taken

The main measurement output of the nephelometer is the aerosol particle optical scattering coefficients (total scatter and backscatter) for three wavelengths − 700, 550, and 450 nm. Additional measurements include sample time, sample air pressure, sample RH, and inlet and sample temperatures.

6.0 Links to Definitions and Relevant Information

6.1 Data Object Description

Starting in 2017, nephelometer data were submitted as routine data with the name aafneph. These data are available in Netcdf format. Previous data sets have the naming structure "nephelometer-air" and are available in ASCII format.

The recorded data fields include (customizable by the user):

> Measurement date/time, sample pressure, sample RH, sample temperature, raw photon counts from different operating modes, scattering coefficients for the three wavelengths from different operating modes (total scatter, backscatter, and zero mode), current operating mode, lamp voltage and current, instrument status flags.

On the G-1, the output data was recorded with 1-Hz resolution with the M300 data acquisition system. The Challenger aircraft will use an updated data system, but the nephelometer datastream will remain the same. Separate data files are normally started for preflight tests and for each flight.

6.2 Data Ordering

Data from the nephelometer can be ordered from http://www.arm.gov/instruments/nephelometer-air. Data are organized by measurement location and campaign.

6.3 Data Plots

These plots are available using the ARM Facility Data Quality Diagnostic Plot Browser (https://dq.arm.gov/dq-plotbrowser/).

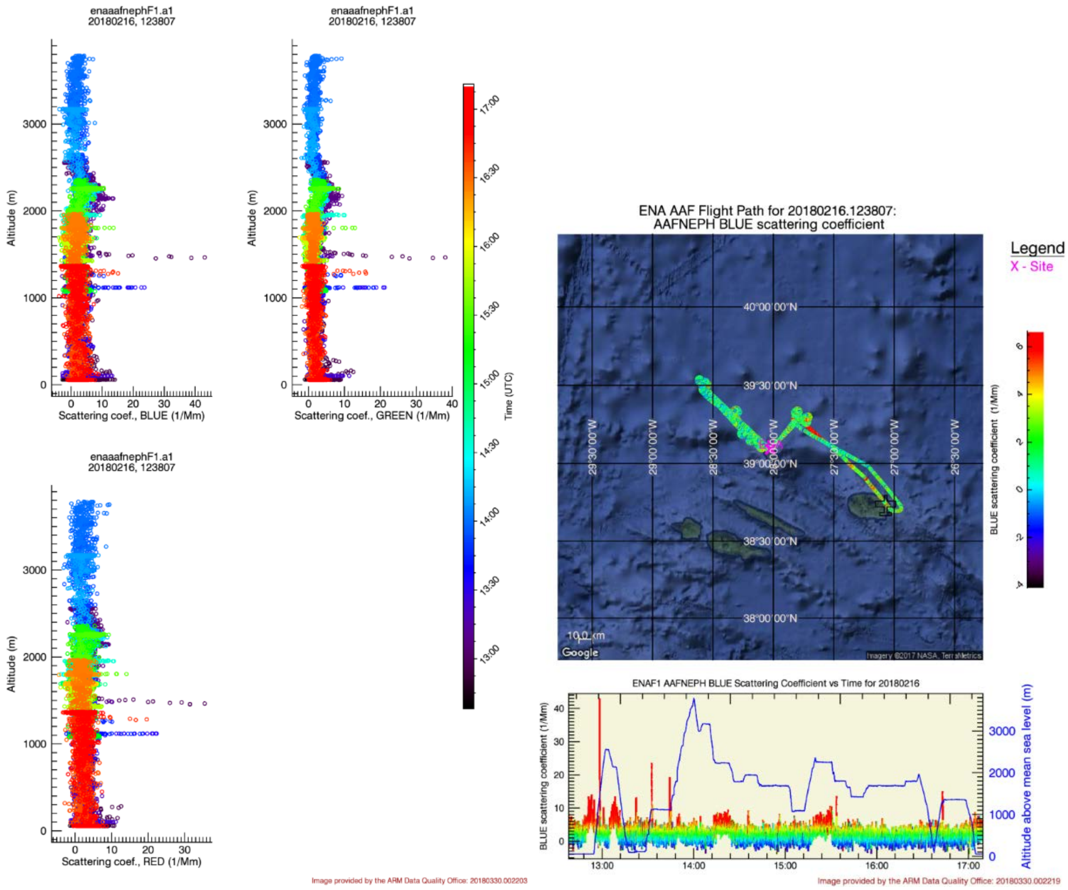

Figure 2. Aerosol optical scattering coefficients (backscatter for three wavelengths) as measured during the Aerosol and Cloud Experiments in the Eastern North Atlantic (ACE-ENA) by the nephelometer aboard aircraft.

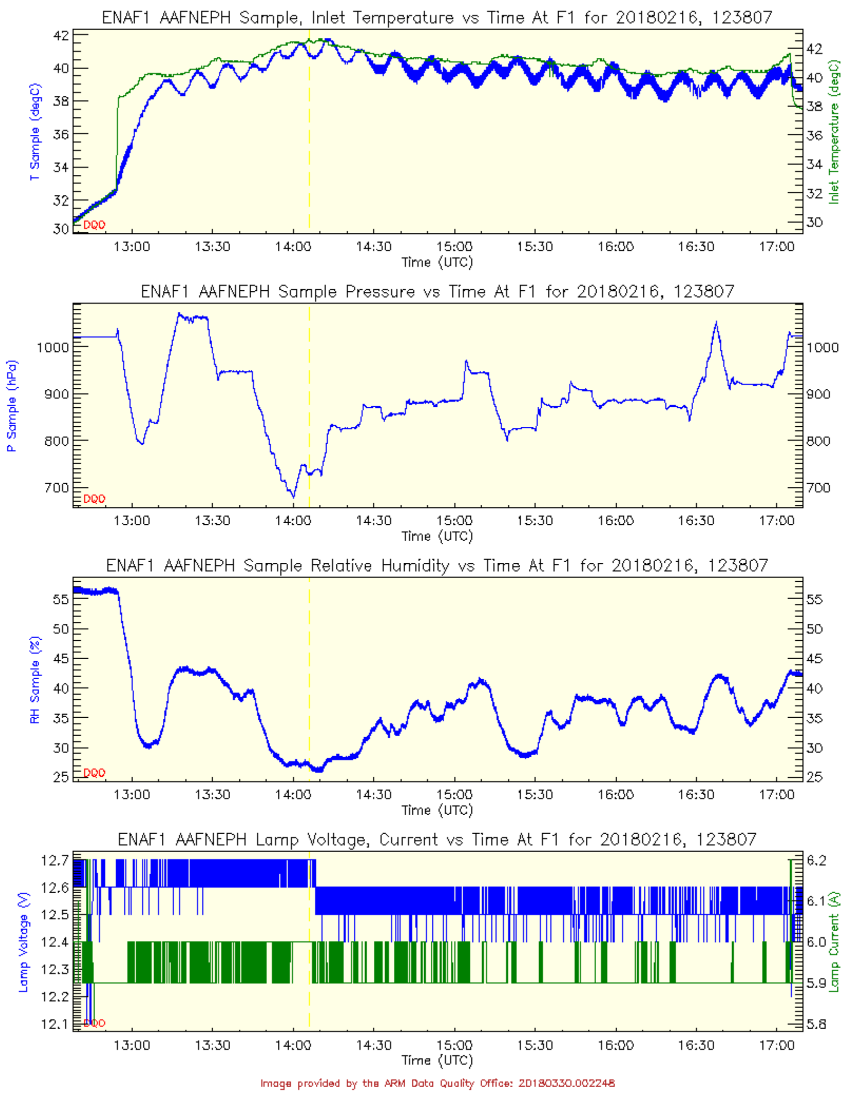

Figure 3. Sample status parameters (pressure, relative humidity [RH], temperature) as measured by the nephelometer during ACE-ENA.

6.4 Data Quality

Data quality evaluation involves automatic flagging of data based on criteria developed by instrument mentors and automatic generation of plots in collaboration with the ARM Data Quality Office.

Automatic data quality checks include:

- Checking the “mode” variable in the nephelometer data to see which operating mode the instrument is in (normal, zeroing) and flagging the data accordingly.
- Ensuring RH levels inside the nephelometer are maintained below 40%.

6.5 Calibration Database

Nephelometer calibration involves measuring the scattering coefficients of dry test gas (CO_2, SF_6, or freon) introduced into the system and comparing them with known values from literature that are adjusted for calibration conditions (temperature, RH, air pressure; Anderson et al. 1996). The instrument is calibrated during service at the vendor or as needed.

The instrument is span-checked with CO_2 before each deployment. A “zero” test is run during preflight preparation before each flight. The results of each calibration are logged by the instrument mentor and AAF’s Director of Engineering.

7.0 Technical Specification

7.1 Units

Aerosol particle optical scattering coefficient: inverse meters (m^{-1}) or inverse mega-meters (Mm^{-1}); relative humidity: percent (%), air pressure: hectoPascals (hPa), temperature: Kelvin (K).

7.2 Range

Upper detection limit for aerosol optical scattering coefficients is 2×10^{-2} m^{-1}. Lower limit is defined by instrument sensitivity (depends on measurement averaging time), which is about 1×10^{-6} for a 1-second measurement.

Angular integration of scattered light is from 7 to 170° in total scatter mode and from 90 to 170° in backscatter mode.

7.3 Accuracy

Accuracy of optical scattering coefficient measurements depends on the accuracy of the nephelometer calibration with CO_2 gas and the instrument’s internal non-idealities, with the latter being the dominant factor. In general, the accuracy is within ±10% (Anderson et al. 1996).

For certain applications an additional source of measurement error has to be considered. This is the angular truncation error, which comes from the nephelometer’s limited angular integration range of 7 to 170° (Anderson and Ogren 1998). The truncation error is 5−10% for submicron particles and 30−50% for particles with sizes between 1 and 10 μm.

7.4 Repeatability

Based on experimental comparison of several nephelometers, the repeatability of aerosol optical scattering coefficient measurements is within ±1% (Anderson and Ogren 1998).

7.5 Sensitivity

Aerosol optical scattering coefficient measurements are sensitive to sample pressure and humidity (Anderson et al. 1996, Anderson and Ogren 1998). No automatic corrections are applied by the instrument and care should be taken when comparing measurement results from different times and locations.

7.6 Uncertainty

For low particle concentrations or short sampling times, random noise is the dominant source of nephelometer uncertainty (Anderson et al. 1996). For typical operating conditions on the aircraft, the detection limit for 1-second average is about 1×10^{-6} m^{-1}.

For particle-scattering coefficients above about 10^{-6} m^{-1} and averaging times longer than about 60 seconds, systematic rather than random sources of uncertainty become dominant. These divide into gas-calibration uncertainties, which are independent of particle size, and uncertainties due to wavelength and angular non-idealities, which are strongly size dependent. The gas calibration contributes about a ±1% uncertainty to particle-scattering measurements. The dominant cause is uncertainty in the scattering coefficient of the calibration CO_2 gas. A larger source of systematic uncertainty stems from non-idealities in the wavelength and angular sensitivities of the nephelometer. Based on modeling and experimental results, the systematic uncertainty is within ±10% (Anderson et al. 1998).

7.7 Input Values

The user can set the nephelometer measurement schedule, which includes operating modes (total scatter and backscatter, different zero measurement modes) and their durations.

7.8 Output Values

The recorded data include:

> Measurement date/time, sample pressure, sample RH, sample temperature, raw photon counts from different operating modes, scattering coefficients for the three wavelengths from different operating modes (total scatter, backscatter and zero mode), current operating mode, lamp voltage and current, instrument status flags.

8.0 Instrument System Functional Diagram

The main components of the instrument are shown in Figure 4. See measurement theory below for details.

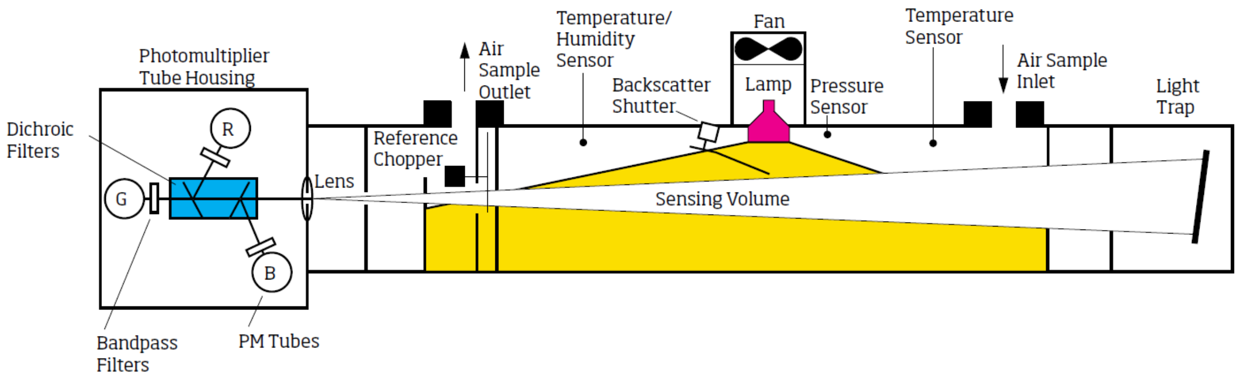

Figure 4. Nephelometer functional diagram. Adapted from the TSI manual.

9.0 Instrument/Measurement Theory

An internal small turbine blower or an external flow system draws an aerosol sample through the large-diameter inlet into the measurement volume (Figure 4). There, the sample is illuminated over an angle of 7 to 170° by a halogen lamp directed through an optical light pipe and opal glass diffuser. The sample volume is viewed by three photomultiplier tubes (PMT) through a series of apertures set along the axis of the main instrument body. Aerosol scattering is viewed against the backdrop of an efficient light trap. The light trap, apertures, and a highly light-absorbing coating on all internal surfaces of the instrument combine to give a low scatter signal from the walls of the instrument.

Dichroic filters, in front of the PMT tubes, split and direct the light, which has been scattered by aerosol. The light is directed into three bandpass filters, blue (450 nm), green (550 nm), and red (700 nm). 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 current that 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.

In backscatter mode, the backscatter shutter rotates under the lamp to block light in the 7 to 90° range. When light is blocked, only light scattered in the backward direction is transmitted to the PMT detectors. The backscatter signal can be subtracted from the total signal to calculate forward-scattering signal data. When this measurement is not of interest, the backscatter shutter can be "parked" in the total scatter position. Periodically (typically for five minutes every midnight UTC), an automated valve built into the inlet is activated to divert the entire aerosol sample through a high-efficiency particulate air (HEPA) filter. This gives a measure of the clean-air signal for the local environment. This signal is subtracted, along with the PMT dark current signal, from the aerosol-scatter signal to give only that portion of the scatter signal provided by the sample aerosol. Particle-scattering parameters for all three wavelengths of total and backscatter signal are continuously averaged and passed to a computer for permanent storage.

10.0 Setup and Operation of Instrument

The nephelometer onboard the G-1 was installed in the aerosol rack and controlled via the main aircraft data system. The instrument was powered from an uninterruptible power supply via a designated switch to prevent electrical interruptions. Instrument zeros were performed by the preflight ground crew via the data system. Data recording was initialized using the data system before take-off.

11.0 Software

Instrument control and data acquisition onboard the G-1was performed by the main aircraft data system (based on M-300). On the Challenger aircraft, the nephelometer will be controlled by an updated data system.

12.0 Calibration

The nephelometer is calibrated by the manufacturer before delivery to the user and during instrument maintenance at the manufacturer's facilities. The instrument mentors perform calibration as needed.

Nephelometer calibration involves measuring the scattering coefficients of dry test gas (CO_2, freon, or SF_6) introduced into the system and comparing them with known values from literature that are adjusted for calibration conditions (temperature, RH, air pressure; Anderson et al. 1996). Calibration coefficients are recorded into internal nephelometer memory and applied to raw measurement data by the firmware.

13.0 Maintenance

Action (when):

- Replacing the halogen lamp (when visual inspection or the software status indicates a lamp failure and before each field campaign).
- Replacing the internal HEPA filter before each field campaign.

14.0 Safety

The nephelometer contains a high-voltage source for the photomultiplier tubes. During normal operation, the user is not exposed to high voltages.

The nephelometer halogen lamp housing may reach temperatures high enough to cause burns. Disconnect power to the nephelometer and allow the halogen lamp and the lamp housing to cool before handling.

15.0 Citable References

Anderson, TL, and JA Ogren. 1998. "Determining aerosol radiative properties using the TSI 3563 Integrating Nephelometer." *Aerosol Science and Technology* 29(1): 57−69, https://doi.org/10.1080/02786829808965551

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