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NAVAL POSTGRADUATE SCHOOL
Monterey, California

NAVAL POSTGRADUATE SCHOOL SHIPBOARD AND AIRCRAFT METEOROLOGICAL EQUIPMENT

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Environmental Physics Group

Naval Postgraduate School
Monterey, California

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The Naval Postgraduate School Environmental Physics Group performs field experiments with both ships and aircraft. Details of the equipment used and calibration procedures are presented.

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Contents

Page

I. Introduction

The Environmental Physics Group (EPG) of the Naval Postgraduate School (NPS) installs and operates meteorological equipment on various research ships and on a research aircraft. The ships that have been used are: RV/Acania, USNS Hayes, USNS Kane, RMS Challenger, and RV/Oceanographer. The aircraft used has been a turbo charged Bellanca, and more recently a Beechcraft Baron, both owned by Airborne Research Associates. The equipment used on all of these platforms is essentially the same.

The purpose of this report is to describe, in detail, the equipment used for the EPG research projects. Such detail is not appropriate for the reports and papers prepared for the projects. This report does not list all of the equipment on the various platforms, only that installed by NPS. In particular all platforms have LORAN-C navigation which is used as an input to the EPG computer system, and the aircraft has a considerable amount of atmospheric electricity equipment, both of which will not be described.

II. General Description

The equipment can best be described as meteorological stations and auxiliary instrumentation. A ship will have one or more stations at various heights above mean sea level and the auxiliary equipment mounted where appropriate so that ship disturbance of the airflow has as little influence as possible. Of course, the aircraft contains one meteorological station and several pieces of auxiliary equipment at a single location. This report will not describe equipment locations as they are adequately described in the individual research reports.

A fully equipped meteorological station has equipment to measure the following parameters:

relative wind speed
relative wind direction
air temperature
dew point
wind speed fluctuation
air temperature fluctuation
water vapor fluctuation

Water vapor and temperature fluctuations are special measurements that are not made on all operations. On shipboard, the true wind speed and direction are calculated from the relative wind speed and direction and the ship's speed and heading. On the aircraft, true wind speed and direction are calculated from the air speed, aircraft heading, and LORAN-C fixes. On shipboard only one level, the highest, is used for wind direction measurements. The auxiliary measurements that are made are:

sea surface temperature
aerosol spectra
inversion height
visibility
ship roll
ship heading

From shipboard sensors the sea surface temperature is determined by both an IR radiometer and a floating thermometer that averages over a depth of approximately 12 inches immediately below the surface. The aircraft uses an IR thermometer.

III. Meteorological Station Equipment (Shipboard)

For a given station, all sensors are mounted on an exposed location, displaced in the horizontal direction a distance of approximately 6 feet, and displaced in the vertical a maximum of 2 feet. All readouts are in a shipboard laboratory; the interconnecting leads to all sensors are in a cable of 27, foil wrapped, twisted pairs. AC power for aspirator motor power is run separately to minimize 60 Hz pickup. Details of the individual pieces of equipment are as follows:

Wind speed and direction: Meteorology Research, Inc., 1022 sensors with 1001 transmuter. The wind direction sensor has dual potentiometers, the amplifier has automatic switching giving a 0-540° continuous readout. The wind speed sensors are cups with a 0.25 m/sec threshold, 60 m/sec maximum speed, and 1% accuracy. For shipboard use the sensors must be equipped with optional salt spray connectors.

Dew Point: General Eastern, 1200AP, with 1211P sensor. The system measures the dew point by the cooled mirror technique. The change in the reflectivity of a cooled mirror upon condensation is detected optically. The optical detector is in a servo circuit which controls the mirror temperature, holding it at the dew point. A platinum resistor, bonded to the mirror, is the temperature detector. The sensor is mounted in an aspirated radiation shield suppled by the manufacturer. The system has a range of approximately 70°C below ambient temperature, which is governed by the capacity of the thermoelectric cooler. Operating temperature limits are 100°C to -59°C.

The response of the system is controlled by the heating and cooling rates (1.6°C/sec). Typical times to come to equilibrium, starting at ambient temperature, are of the order of 15 sec, which includes normal system servo oscillations. Manufacturer stated accuracy is ±0.22°C.

The platimum thermometer comes equipped with a three wire hook up for the readout that is supplied with the instrument. The readout converts sensor resistance (three-wire) to a voltage proportional to temperature. Because of drifts in the voltage conversion circuitry, we now read the sensor resistance with a computer controlled 4-wire Ohmeter and convert to temperature in computer software. The Ohmeter and the supplied readout cannot be used at the same time. Converting the sensor to a 4-wire system has eliminated lead resistance influence.

Air temperature: Rosemount, 100 Ohm platinum resistors, 4-wire configuration. The resistance is measured with the same computer controlled meter used for the dewpoint measurements. The resistor is mounted in a 1/4 in stainless steel tube. This tube fits loosely in a 3/8 inch tube topped by a small metal enclosure. The enclosure has an environmentally tight screw cap so it may be opened for access to the resistor leads. The outer tube and housing are part of an R.M. Young, Gill aspirator. The aspirator consists of a silvered glass dewar which is isolated from the heat of the aspiration motor by a long tube. To improve the performance of the aspirator we have mounted a silvered mylar radiation shield at the inlet. This has been found to be especially necessary on shipboard where some sensors are over the water and some over the warm deck of the ship.

In order to eliminate contact e.m.f. problems the 4 wires to the resistor are continuous all the way to the ohmeter. Solder connections are made in the aspirator housing. All solder points are at the same temperature so that thermal e.m.f. is not a problem. The accuracy of the system is ±0.2°C, the uncertainty being due to imperfect aspiration. In order to achieve this accuracy with the 100 ohm platinum resistor the ohmeter must have 5 significant figure accuracy.

Wind Speed Fluctuation: Thermo Systems, Inc. (TSI), 1210 probe mounted with a platinum film on a 60 m diameter, 2mm long, cylindrical quartz substrate. Nominal resistance is 6 ohms. The detector is a TSI 1054B constant temperature anemometer bridge. The dc level from the bridge is removed with a TSI 1057 signal conditioner, and a TSI 1056 variable decade is used as the balance resistor. Frequency response of the sensors is 500 Hz at 30% overheat.

The sensors are mounted in holders into which they can be withdrawn when not in use. The holder has a lock nut to maintain the axis of the cylinder in the vertical direction so that it is not sensitive to the vertical component of the wind.
The holder is mounted on a wind vane, the purpose being to keep the sensors foreward of any obstructions that create local turbulence. All turbulence sensors at a given level are mounted on the same vane.

In order to restrict the signal analyzed to the inertial subrange, bandpass filtering is used. The lower cutoff frequency is always 5 Hz, the upper frequency varies from 70 to 200 Hz.

The lower value is used when 60 Hz harmonics are a noise problem. The signal conditioners are not sufficient for the band pass filtering and various models of KH Kron-Hite filters are used in addition.

Temperature Fluctuations: The sensors are TSI 1210 probes mounted with 2.5 um platinum wire; nominal resistance is 50 ohms. The detector utilizes a Sylvania 140 thermosonde board. The bridge in the detector uses a 3000 Hz carrier frequency at a very low current to minimize sensor heating. Bridge current is 50 μAmp, giving a heating rate of 0.1 μWatt, which has negligible affect on the sensor temperature. Frequency response of the bridge-sensor combination with 100 ft lead length is 800 Hz which is beyond the range of interest.

The bridge contains provision for automatic balancing so that changes in the mean air temperature do not take the bridge beyond its operating range. The balance has a total range of approximately 2 ohms, but the bridge calibration will change as the automatic balance is used to zero out more than a 1 ohm change. The balance has a very slow response, approximately 3 sec, so it has no affect on the response to rapid temperature fluctuations.

Rather than use frequency filtering to restrict the accepted signal to the inertial subrange (as is done for the velocity fluctuations) spatial filtering is used. Two probes are used, separated by a distance of 30 cm. These probes are connected to the sensor and reference arms of the thermosonde bridge. In this manner the difference in the temperature at two points, separated

30 cm in a direction transverse to the air flow, is obtained.

Water Vapor Fluctuations: Electronic Research Corporation, Lyman-α cell. This system operates by determining the absorption of ultraviolet light by ambient water vapor. The 1215 Å Lyman-α transition of hydrogen is the source used. The source and receiver tubes have ultraviolet transparent MgF windows which, unfortunately, are also slightly water soluble. The system does not last long in a shipboard marine environment. The sensor is mounted on a wind vane which keeps it aligned in such a way that source heating does not modify the ambient humidity in the air gap. The source and detector windows are placed a distance of 1 cm apart, giving an active volume of approximately 1 cm^3.

For some applications it is necessary to measure the temperature-humidity fluctuation covariance. When this is done, a single microthermal sensor of the type described above is mounted immediately above the Lyman-α cell so that any heating from the unit does not affect the sensor. A thermosonde bridge is used as the detector with a TSI 1056 decade as the balance resistor. Frequency filtering of the thermal fluctuation signal is done in the same manner as described for the velocity fluctuations.

IV. Shipboard Auxiliary Equipment

Of the equipment to be described below, only the sea-surface temperature and inversion height are measured on all research operations.

Sea-Surface Temperature (immersed sensor): The sensor is a 100 ohm platinum resistor and is identical to that used for air temperature. The sensor is enclosed in a long streamlined float that can be either towed at normal ship speed or remain near the surface when the ship is stopped. The float is a 12 ft long, 3/4 in internal diameter tygon tubing. One end of the tubing is sealed with a brass plug and the sensor is mounted in this plug with good thermal contact. The other end, through which the lead passes, is sealed by silicone cement. The plug extends 1 inch beyond the end of the tubing so that it makes good thermal contact with the water. The tubing is not allowed to float freely on the water; it is suspended from a line, the length being in the water depending on the ship speed. The line is extended from the side of the ship by a guyed pole to extend the sensor to a region that is outside the ship's influence.

Sea-Surface Temperature (IR radiometer): Barnes, PRT-5 Radiation Thermometer. The instrument has an accuracy of 0.5°C (according to manufacturer), a sensitivity of 0.1°C, and a response time of 5 milliseconds. The mounting position on the ship is very critical. We place the sensor unit foreward, in an elevated position, so that the ships wake is not in the field of view. Occasionally the roll of the ship will cause viewing of the wake. It is not clear which angle is best to use for the line of sight. If the Brewster angle is used, reflected cloud radiance is minimized. However, the roll of the ship causes maximum noise at this angle if clouds are present. As a compromise we have chosen to operate at an angle of 45°.

Inversion Height: Aerovironment 300, Acoustic Radar with 100 Watt driver. The device has a range of 100 to 1000 m, but it is difficult to discern an inversion above 700m. The noise encountered on shipboard when underway limits the useful range to about 500m. The enclosure used for the antenna is the standard design, a pentagon with sides 4 ft wide and 8 ft high. For shipboard the base of the enclosure must be soundproofed the same as the sides. The recently available toothed enclosure extensions, Thenadners, also reduce the noise considerably. The enclosure is normally located toward the stern of the ship to cut down on wind noise, and in a location where stack noise is minimal.

Aerosol Spectra: Three particle measurement systems spectrometers are used to cover the size range 0.1 to 150 µm radius. The ASASP divides its full size range into 4 ranges of 15 size bins each, the CSASP into 2 ranges of 15 bins each, and the OAP into 30 bins. The probes are operated by a DAS64 data acquisition system. The DAS automatically cycles the probes and ranges, spending equal time on the ASASP and CSASP and twice as much time on the OAP. Also twice the time is spent on the large size ranges of each probe to improve counting statistics for the large sizes. Except for fog or bad haze conditions, the number of counts in the large size ranges is adequate but smaller than desireable. A larger proportion of the time spent on larger sizes would help.

The probes are always mounted on a mast, in an exposed location, away from ship influence as much as possible. The probes must be available for occasional cleaning of the optics so the location used normally will not be as good as for the meteorological station.

Visibility: Meteorological Research, Inc. 1580 Fog Visiometer. The device covers the visibility range 100 m to 20 km. It is used as a monitor to indicate conditions, not for quantitative measurements.

Ship Heading: On the RV/Acania a Librascope 7070 analog to digital converter has been connected to the gyroscope used for ship navigation. The converter is a mechanical device that senses the readout angular orientation. A buffer interfaces the serial output of the converter to a 16 bit interface to the computer.

Ship roll and Roll Rate: A mechanical pendulum geared to a potentiometer, placed on and pivoting about the roll axis of the ship, provides an analog signal proportional to the ship's roll angle. A simple RC network is used to differentiate this signal to yield an output related to roll rate. The rate of roll is useful, for example, in compensating for the effect of roll on the measurement of the standard deviation in wind direction. Errors introduced by vertical and lateral accelerations of the ship are minimized by placing the pendulum on the roll axis and midway along the length of the ship.

V. Aircraft Equipment

As was mentioned above, much of the aircraft equipment is the same as on the ship. Besides the meteorological parameters that have been described, the aircraft also carries equipment for atmospheric electricity measurements, electric field and conductivity. This equipment will not be described here. For the equipment listed below most of the needed detail can be found in the shipboard system descriptions. The following will describe important differences and equipment that is unique to the aircraft. Equipment that is identical to shipboard will not be described.

Temperature and wind speed fluctuations:

Both utilize 4.5 μm tungsten wires rather than the platinum wire and films used on the ship. The wires are needed rather than the films because vortex shedding from the sensors distorted the signals at aircraft air speeds. The tungsten wires are much sturdier than the platinum wires which break frequently during aircraft operation.

Temperature fluctuations are measured with TSI model 1044 DC bridges. When the turbulence sensors were first installed on the aircraft, excessive noise was encountered due to acoustic noise from the propeller. Three foot extensions were placed on each wing tip and the probes placed on the ends of the extensions. The increased distance from the prop (18 ft) solved the problem. The temperature fluctuation probes are separated by a vertical distance of .8m for spatial filtering. The noise level of this system is about 3 mK rms.

Sea Surface Temperature

The radiometer is a PRT-5 as is on the ship but its interpretation is slightly different. When the aircraft is low (10 ft above the sea surface is one of the heights used) reflected radiation from the airframe is significant. This always raises the recorded temperature slightly and a correction must be applied.

Wind speed and direction:

The relative air speed is determined by a MKS Inc. capacitive differential pressure transducer, model 223A. The aircraft normally flies with the average relative wind directly on the nose. The aircraft true ground speed and direction is determined with a Teledyne 711 Loran C navigation system. True wind speed and direction are calculated by the onboard computer. The air speed is accurate to 0.5 m/sec, the true wind speed accuracy depends on the averaging time but is about 1.0 m/sec for a two minute run.

Air temperature: Rosemount total temperature aircraft probe in a 102E housing. The probe is mounted in the window on the left side of the aircraft.

Dew Point: EG&G model 137 aircraft system. The cooled mirror principle is used (similar to the ship system but specifically designed for aircraft use).

Altitude. Altitude is determined by sensing the pressure with a solid state device and also by radar altimeter. The pressure sensor is a National Semiconductor type LX1702AN.

Microwave refractive index: Airborn microwave cavity refractometer supplied by the Naval Air Center (Indianapolis).

VI. Data Acquisition -

Three basic methods of data acquisition and shipboard analysis are used: 1) Computer controlled acquisition of all signals, 2) Analog tape recording and strip charts, and 3) Spectral analysis. Spectral Analysis: Nicolet Scientific Corp., 440B Spectrum analyzer. This is a small, fairly easily portable analyzer which is ideal for field work. We have found that spectral analysis is a necessity on shipboard, particularly to monitor fluctuation signals. A ship is a noisy environment, and the noise encountered is not a constant. Spectral analysis can help solve noise problems and frequent monitoring of signals to verify the quality of the data is advisable.

For measurement of temperature-humidity covariance, an HP dualchannel spectrum analyzer is used. Results are recorded on an X-Y plotter for later analysis.

Analog recording: Honeywell 5600E tape recorder. This unit has 14 analog channels and automatic speed control. We have built a selector so that all 14 input or output channels can be monitored on a oscilloscope and by spectral analysis. The recorder is a back up device, all analog signals being recorded in case there is a failure in any other portion of the data acquisition system.

Strip chart recordings are made of the relative wind direction, temperature fluctuation rms, wind speed fluctuation rms, and one other signal as desired. The strip chart allows post analysis of the data to be done to pick out times where external influence could invalidate the direction changes. The strip charts allow these events to be detected (recognizing that qualified personnel may not be available for continuous 24-hour monitoring).

Computer controlled acquisition: Hewlett Packard (HP) 9825 or 9835 desktop computer and HP 3052A data acquisition system. The data acquisition system includes a 59309A digital clock, 3455A digital voltmeter, and 3495A scanner. Data output is on the computer internal tape and a 9871A or a 2631 printer.

The scanner has 40 channels of low thermal relays with a switching time of less than 10M sec and a contact differential emf of less than 2 u Volt. The relays are three terminal accommodating a hi, lo, and ground or guard. This is very desireable since the guards for the various signal channels can be kept independent, eliminating ground loops.

The voltmeter has six significant figures resolution, which is needed for the platinum resistance thermometer measurements. Accuracy with the high resolution off is 0.001%.

The interface between the computer, data acquisition system, and printer is the HPIB (IEE-488-1975). In addition the computer is interfaced with the buffer for the LORAN-C navigation and the ship heading indicator by a 16 bit interface. The computer alternately operates the scanner, interrogates the voltmeter, and interrogates the buffer. All scanner channels are activated and the data acquired between individual readings of the direction. The ship position is read every 5 minutes.

Normal shipboard procedure is to produce 1/2 hour averages of all signals. The exact number of samples of each channel depends on the program being used, e.g. some programs do many more calculations and intermediate averages. The number ranges from 800 to 1500, and the computation plus print time from one to two minutes.

During the 1/2 hour cycle all signals are acquired, averaged, computations made and all averaged voltages and computed parameters are stored on the tape and printed out. Included in the storage and printout are all system calibration parameters so that all calculations can be reperformed later, if needed.

<u>Aerosol Computer System</u>: One Hewlett Packard computer is dedicated to interfacing with the aerosol data acquisition system. This is necessary for two reasons: 1) The DAS64 does not operate in the handshake mode and 2) Operation of both the meteorological and aerosol programs would take too long for a single computer. Interfacing between the DAS64 and the computer is done by a 16 bit interface. The data acquisition system is operated on the slowest mode so that it outputs a record every 40 seconds. The data are read directly into the memory of the computer, a portion of the memory having been assigned as a buffer for this purpose. When the buffer is full, the buffer data are added to the correct storage locations in the computer for averaging and calculations once the 1/2 hour averaging period has elapsed. Again all data and computed parameters are stored on tape and printed.

<u>Hybrid Meteorological-aerosol System</u>: We have had the DAS64 aerosol data acquisition system equipped with "housekeeping modules", which are available from the manufacturer. These modules allow up to 12 channels of analog data to be acquired, digitized, and output as part of the DAS64 record. In this manner meteorological data can be made available to the aerosol computer for a hybrid, if simplified, dual purpose program.

The housekeeping modules do not have sufficient precision to read the resistance of the platinum thermometers.

Fluctuation rms signal: The primary analysis technique for the fluctuation signals is through the rms value. The circuitry to do this has been built around Analog Devices 440J rms operational amplifiers. The output has a 30 sec time constant and the system has variable gain from 1 to 100 in a factor of 3.3 steps.

VII. Calibration Procedures

Air, Sea and Dewpoint Temperatures: All temperature sensors are calibrated together in an insulated chamber. The air and sea temperature probes and a HP2801A quartz thermometer standard are mounted in an aluminum cylinder which effectively eliminates the temperature differences between these sensors. The differences are less than 0.01°C. The dewpoint thermometers cannot be mounted in the same block because they are permanently mounted to the mirror in the sensor. In the chamber we use for calibration, these sensors can be as much as 0.1°C away from the cylinder temperature. The temperature measured by a sensor is found from its resistance by inverting the standard equation

$$R = R_o(1 + \alpha T) \qquad (1)$$

where T is in °C, R_o the resistance at the ice point, and α is the temperature coefficient. For the air temperature sensors $\alpha = 0.003921$, and $\alpha = 0.003895$ for the dewpoint sensors. The calibration procedure is to determine the values of R_o for each sensor from the known temperature and the measured resistances. This is done at several temperatures to check for errors which can be introduced by temperature inhomogeneities in the insulated chamber.

IR Sea-Surface Temperature: The sensor is placed approximately 1 ft above a stirred water bath. The water bath temperature is determined by a quartz thermometer. Calibration is performed indoors so that reflected radiation from the warm walls of the room bias the IR reading high. A bias of 0.3°C, compared to calibration under a night sky results. Calibration is performed at several temperatures from 0°C to 80°C, and the inaccuracy is around ±0.2°C.

Wind Speed: Calibrations are occasionally performed in one of the NPS wind tunnels but they are of dubious value for other than detecting errors of greater than 1 m/sec. Actually, given the accuracy of the cups, the calibration is more one of the wind tunnel. We have not found any detectable errors, or differences between sensors, within 0.5 m/sec. The exception is when the bearings on a sensor age and this is easily detected long before the calibration is affected by observing the decay rate of the shaft rotation when no cup is in place.

Visibility: No calibration is performed other than the internal calibration of the instrument.

Aerosol Spectra: The instruments are sent to the factory for periodic calibration as NPS has no facilities. Comparison of predicted optical extinction with values measured on the NPS over-water optical range show agreement within a factor of two.

Inversion Height: The acoustic sounder records are calibrated with radiosondes every 12 hours during most shipboard operations.

Temperature Fluctuation: The thermosonde is set up to give a sensitivity S = 20 volt/ohm. This is done by balancing the bridge with a sensor and a Dekabox DB62 precision resistance decade. The bridge current and gain are adjusted to give the desired sensitivity for 0.01 Ohm resistance steps. Best signal to noise for the system is obtained by keeping the bridge current as high as possible and the gain low.

Differentiating the resistance versus temperature formula, Equation 1, and taking bridge sensitivity into account, the change in bridge output voltage dV due to a temperature change dT is given by

$$dV = dT/\alpha S R_o \qquad (2)$$

Here R_o is the resistance of the sensors at 15°C and $\alpha = 0.0036$ $^\circ C^{-1}$ for the sensors we use.

Wind Speed Fluctuations: Two types of calibration are performed: in-situ and laboratory. The in-situ calibrations are preferred because sensor aging has no effect. For every 1/2 hour averaging period the mean wind speed from the cup and the fluctuation voltage are determined for each 10 sec. The 1/2 hour mean values and their variances from both sensors are compared to determine the fluctuation sensor calibration. Laboratory calibrations are performed using a TSI 1125 calibrator. The unit has a pressurized chamber with a small exit orifice with a diameter that is nearly equal to the sensor length. The air speed in the orifice is determined from the chamber pressure using data supplied by the manufacturer. Very accurate pressure measurements are made using an Ellison inclined draft gauge.

Calibration parameters are obtained by fitting the bridge output voltage versus air speed data with the curve

$$V^2 = V_o^2 + B\sqrt{U} \qquad (3)$$

where V is the voltage and U the air speed. V_o and B are determined by fitting the data in the air speed range 2 - 20 m/sec so

V_o is not the voltage at zero wind speed. This is done because the fit is not good at very low wind speeds. Differentiating the above equation gives the wind fluctuation in terms of the measured voltage fluctuation

$$U' = [4V \quad U /B]V' \tag{4}$$

where the prime denotes the fluctuating component and the bar the average value.

<u>Water Vapor Fluctuations</u>: In order to calibrate the Lyman-α system, the water vapor content between the source and detector must be varied in a controlled manner. Since the system is used to measure fluctuations, it is not necessary to know the absolute water vapor content, only the change. This is especially important since source and receiver windows are subject to aging, which changes the transmitted light level, but does not change the fluctuation calibration.

Since the light is extinguished by the water vapor the output voltage is given by

$$V = V_o \exp(-\lambda Q) \tag{5}$$

where Q is the total water vapor between the windows and V_o and λ are calibration constants. The voltage change dV is related to the water vapor change dq by

$$dV_o = -\lambda V dQ \tag{6}$$

We change Q by changing the source-receiver spacing, dl. The only drawback to this procedure is that the source-receiver solid angle changes. This effect has been measured by Arden Buck of NCAR. Writing A(l) as the effective area of the transmitted light

$$Q = A(L)qL \qquad (7)$$

where q is the water vapor density. Differentiating Equation 7 and substituting into Equation 6 gives

$$dV = -\lambda Vq[A(L) + L\frac{dA(L)}{dL}]dL \qquad (8)$$

q is determined from the **dewpoint** sensor. Thus, the change of V with L allows the calibration parameter λ to be easily determined.

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