Wind Tunnel Tests of the Met One/ATI Model 50.5 Ultrasonic Wind Sensor

by

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Abstract

The Met One/ATI Model 50.5 ultrasonic wind sensor was subjected to a limited number of wind tunnel tests to determine suitability for use in ATG's field studies. These tests included an evaluation of the wind speed and direction measurements through a random, "unobstructed" angle of attack (with respect to the sensor heads) and along the axes of the sensor ("obstructed"). Tests were conducted in ATG's wind tunnel over a controlled airflow rate from about 0.25 m/s to about 24 m/s.

In the unobstructed tests at lower speeds, wind speed errors were relatively small (< 0.1 m/s) and slightly negative below 4.7 m/s but increased up to about 0.4 m/s through 24. m/s. The errors appear to be reasonably predictable based on an R-squared value of 0.945 for a logarithmic fit for the data. Unobstructed wind direction measurements were within 1.5° at speeds over 3.5 m/s, but errors increased to several degrees as speeds were lowered to near 0.25 m/s. The wind direction measurement pattern appeared to follow a logarithmic function with an R-squared value of 0.7354.

Obstructed wind speed tests of the Model 50.5 were made along the four axes where the transducers obstruct the natural flow of air through the sensor: 0°, 90°, 180°, and 270°. Interestingly, all of the data recorded by the Model 50.5 were less than the tunnel speeds except near 24 m/s where the Model 50.5 surpassed the tunnel flow rate. Differences were negative with a decrease in magnitude up to 14.5 m/s but were positive at the upper tunnel flow rate. The best fit to this relationship is a second order polynomial with an R-squared value of 0.7297. Calculation of the percent differences indicated that most errors were less than 10%, and the largest errors were observed at the lowest flow rates of the tunnel. The obstructed wind direction measurements indicated that the largest differences occurred at flow rates below about 2.3 m/s. The magnitude of the maximum errors was consistent with the errors noted in the unobstructed angle of attack.

Overall, the most noticeable wind speed and wind direction errors occurred below about 2.3 m/s. These errors appear to be predictable for wind speed and, to a lesser extent, for wind direction. A more thorough analysis among several individual Model 50.5 sensors and using more angles of attack may possibly lead to a better quantification of these errors. With additional data, better predictive error functions could be formulated and applied to minimize errors within the signal processing components of the sensor.

OPTICAL CHILLED MIRROR DEW POINT HYGROMETERS

BACKGROUND

Optical Chilled Mirror (OCM) Hygrometers are instruments designed to measure the dew/frost point temperature of a gas mixture. Dew Point Temperature is the saturation temperature to which any gas mixture must be cooled at constant pressure so that it will be saturated with respect to water. Frost Point Temperature is the saturation temperature to which a gas must be cooled at constant pressure so that it will be saturated with respect to ice.

Since saturation vapor pressure is a unique function of the temperature, determining the temperature at which water vapor begins to condense on a cooled surface is equivalent to a measurement of its partial pressure. At equilibrium, the water vapor partial pressure of the condensate is equal to the water vapor partial pressure of the gas mixture.

Optical Chilled Mirror Hygrometers use a cooled mirror as the surface where condensation takes place(figure 1). Utilizing Electro-optic circuitry, the instrument precisely determines the formation of condensate (dew or frost), and by means of a Temperature Transducer (PRT), the Dew Point Temperature or the Frost Point Temperature is accurately measured.

Optical Chilled Mirror Hygrometers are designed to continuously monitor the moisture in a gas sample. They utilize the output of the electro—optic circuitry (which senses the mirror surface optical characteristics) to servo the electrical current through a Thermo-electric Cooler Module (the devices used to chill the mirror surface)(figure 2), so that dynamic equilibrium between water in two of its natural states (water vapor and dew or water vapor and ice) is precisely maintained.

ACCURACY OF THE MEASUREMENT

Webster defines ACCURACY as “freedom from error or absence of error". The purpose of any measurement is to determine the TRUE VALUE of the quantity being measured. Error is the difference between the true and the measured quantity.

The Instrument Engineer's handbook provides the following definitions: ACCURACY is the degree of conformity of an indicated value to a recognized accepted standard value or ideal value. ACCURACY RATING is the number or quantity that defines a limit that errors will not exceed when the instrument is under specified operating conditions. Accuracy rating includes the combined effect of conformity, hysteresis, dead band, and repeatability errors.

CONFORMITY ERROR is the maximum deviation of the calibration curve from a specified characteristic curve so positioned as to minimize maximum deviation.

HYSTERESIS ERROR is the property of an element evidenced by the dependence of the value of the output, for a given excursion of the input, upon the history of prior excursions and the direction of the current traverse.

DEAD BAND ERROR is the range through which an input can be varied without initiating observable response.

REPEATABILITY ERROR is the closeness of agreement among a number of consecutive measurements of the output for the same value of the input, under the same operating conditions, approaching from the same direction, for full range traverse. It does not include hysteresis.

Hence, the accuracy specification of an OCM hygrometer should account for conformity, hysteresis, dead band, and repeatability errors. Since the instrument is based upon measuring a primary quantity, there is no humidity transducer and hence conformity errors DO NOT EXIST (there is no calibration curve to deviate from). There are no known hysteresis no dead band phenomena associated with the evaporation or condensation of water.

In an Optical Chilled Mirror Hygrometer, the sources of error are:

1. Phenomena occurring at the reflective surfaces.

2. Temperature measurement and display differences.

Errors occurring at the Reflective Surface

The KELVIN EFFECT is the phenomenon described by the variation (REDUCTION) of the Dew Point Temperature due to the presence of droplets on the mirror surface that is not flat, INCREASING the mirror vapor pressure (due to the surface tension forces of the droplets) and REDUCING the temperature required for a given gas sample content.

The magnitude of the KELVIN EFFECT is a function of the mirror surface condition and treatment, and of the fraction of dry mirror reflectance chosen for the operating point. A small fractional reflectance is obtained with a larger mass of water, resulting in reduced error due to the KELVIN EFFECT. This is referred to as operating the instrument with a heavy dew layer.

The RAOULT EFFECT occurs when the presence of soluble contaminants at the mirror surface DECREASES the vapor pressure at the mirror surface for a given temperature. This translates into a reading of a HIGHER dew point temperature. The magnitude of the effect is proportional to the concentration of solute and is dependent on its chemical composition. Operating the hygrometer with a thicker dew layer means that, for a given amount of contaminant present on the mirror surface, the greater mass of condensate will have a reduced concentration and, consequently, less error.

It is interesting to note that the error induced by the KELVIN EFFECT and the error induced by the RAOULT EFFECT have opposite signs, resulting in a cancellation effect. Operating the hygrometer with a thick dew layer minimizes both types of errors.

Accuracy of the Temperature Measurement

The sources of error in temperature measurement (utilizing a Platinum Resistance Thermometer) and display are:

1. Temperature gradient from dew surface to mirror surface.
2. Temperature gradient from mirror surface to thermometer.
3. Temperature error from self—heating of the thermometer element due to the excitation current.
4. Temperature error due to thermal conductance of the thermometer leads.
5. Temperature error due to readout calibration nonlinearity.

These errors depend upon the operating parameters (mirror temperature, sample flow rate, and the temperature of the instrument), the geometry of the mirror, the type and size of the temperature transducer, and the techniques utilized to display the temperature data.

OPERATION AND MAINTENANCE

Most OCM Hygrometers are designed to operate continuously and feature microprocessor-based electronics. The numerical processing capabilities of the processors in turn makes psychrometric data reduction (that is the ability to express the moisture contents of a gas mixture in several different units) possible. These instruments offer digital readouts, analog and digital temperature, and of interfacing with pressure transducers (sample pressure and sample temperature are needed for psychrometric data reduction).

Optical Chilled Mirror Hygrometers generally and characteristically suffer from the inability to differentiate between dew/frost and particulate contaminants on the mirror surface since both phenomena manifest as a loss of reflected light. The "cure" for this problem has traditionally been cleaning the reflective surface "the mirror" "fairly" often and/or "balancing" the instrument.

Cleaning the mirror involves heating of the surface and physically removing the particulate matter and contaminants from it. It obviously interrupts the normal monitoring of moisture.

Balancing the instrument (manually or automatically), basically consists of nulling the variations in the Electro-optic sensing scheme due to contamination on the mirror surface.

One main concern to the user is the frequency at which maintenance operations (balance operations and/or physical cleaning of the mirror are to be performed. There are two key determinants to this frequency: a) the design of the instrument, and b) the quality and condition of the sample stream.

The design parameters that affect the maintenance frequency are as follows:

1. Topology of the Electro-optic sensing scheme
2. Wave length of the radiation source(s)
3. Spectral response of the receiver (s)
4. Optical quality of the reflective surface
5. Sensor geometry
6. Robustness of the control algorithm

A detailed description of the mechanisms of how these design consideration affect maintenance frequency is beyond the scope of this paper. Suffice it to say that the frequency spans from a few days (in most commercially available instruments) to several months in the most advanced OCMs.

The quality and condition of the sample stream has a direct impact on the maintenance schedule. A sensor exposed to a clean, contaminant-free stream will require substantially less attention and care than a sensor monitoring a "dirty" stream. The quality of the sample system and filters play an important role in the determination of this schedule.

LIMITATIONS OF THE TRADITIONAL OCM TECHNOLOGY

As indicated in the previous section, with the traditional sensing scheme the ability of the hygrometer to perform is limited by the invariance of all the components in the sensing loop; i.e., that the "predetermined reflectivity loss" be only a consequence of the presence of dew or frost on the mirror surface, and nothing else. In other words, the instrument is not able to determine if a variation in the optical signal is due to 1) condensate coalescing on the mirror surface; 2) a variation in the characteristics of the Electro-optic components (due to aging, temperature coefficient, or any other reason;) or 3) the mirror surface reflectivity changing due to the deposition of contamination.

Obviously, the effort in industry has been to ensure that the time invariance of the sensing loop is indeed achieved; that is, whenever the reflectivity of the mirror is lower than the one at original calibration, the difference is due to the presence of dew or frost. Consequently, different schemes ranging from manual adjustment BALANCE MODE to AUTOMATIC BALANCE CONTROL with a plethora of acronyms were developed. Still, these are all approximations to the ideal realization. MANUAL BALANCE, for instance, requires operator intervention, i.e.: the Electro-optic sensing loops parameters are "tweaked" to ensure original values.

In more sophisticated (and expensive) implementations, the instrument does the tweaking automatically. In one case, the "balancing" is event triggered, i.e., an operator throws a switch to initiate the sequence. In another case, "balancing" is a time—driven event. Every so many hours, the instrument will automatically initiate the balancing sequence, regardless of the need for it. Furthermore, regardless of how the balance (or proper acronym) is initiated, it involves the heating of the mirror surface to a temperature higher than the prevailing dew (frost) point, to ensure a dry (highly reflective) mirror surface as the initial condition for any readjustments.

Why are these realizations sub-optimal? There are three key reasons. First, whenever the OCMH goes (or is put) into a balance mode, the instrument cannot measure dew (frost) point. It is not an on-line measurement anymore. Remember instruments will hold the output at the LAST measured dew (frost) point temperature. Should a change in the moisture contents of the gas occur while the instrument is in the balance mode, it will go undetected for as long as the instrument is in this mode.

The second key reason involves the parameter that initiates the balance sequence. For an EVENT TRIGGERED SEQUENCE, an operator (probably following a maintenance schedule) will initiate the sequence periodically, at predetermined (usually programmable) intervals of time. Both triggering mechanisms fail to identify the need for a readjustment of the Electro-optic sensor loop. The instrument could need adjustments much more often than the intervals arbitrarily established.

The third key reason, and probably the most important from the user's standpoint, is the inability of classical OCMHs to deal with contamination deposits on the mirror surface. CLASSICAL OCMHs ARE UNABLE TO DISCRIMINATE BETWEEN DEW (FROST) AND CONTAMINANTS, and hence are unable to operate for long periods of time without physically cleaning the mirror surface, freeing it from particulate matter deposits.

The NEW Patented EdgeTech DewTrak SENSING SCHEME

(Technologies in this section of the paper are protected under US Patent 4629333)

EdgeTech's new sensing technology allows OCM Hygrometers to differentiate between dew and contaminants and to continuously online automatically adjust the circuitry to compensate, without the interruption of the normal operation, for the variations in the Electro-optic sensing scheme due to the presence of contaminants on the mirror surface as well as for the aging of sensor components.

This unique technology provides continuous and automatic diagnostic signals relaying the status of the Electro-optic circuitry. The instrument signals when and if the mirror needs maintenance.

This new sensing scheme deals effectively with the main limitations historically associated with OCM technology because it provides:

1. TRUE CONTINUOUS OPERATION
2. DIFFERENTIATION BETWEEN DEW/FROST AN CONTAMINANTS
3. MEASUREMENT FREE FROM CONTAMINANT INDUCED ERRORS
4. MEASUREMENT FREE FROM COMPONENT AGING INDUCED ERRORS
5. MINIMUM PREVENTIVE MAINTENANCE

PRINCIPLE OF OPERATION

The sensing scheme is based upon the fact that dew and frost have scattering properties and upon the fact that particulate contaminants reduce the amount of energy the mirror reflects.

When a highly collimated radiation beam is focused onto a dry mirror surface, the energy will be reflected according to Snell's law of reflection(figure 3). When the mirror surface is at the dew/frost temperature, the incident radiation is not reflected anymore, instead it is refracted in all directions by the dew droplets or the frost icicles that have formed on the mirror surface. When there are particulate contaminants on the mirror, the amount of reflected energy is reduced, but the geometrical distribution is not drastically changed (most of the energy leaving the mirror is concentrated in Snell's cone)(figure 3).

Two photo-detectors located in vary critical positions around the mirror are used. One, the "DIRECT PHOTODETECTOR," is located in the center of the base of Snell's cone, i.e., at the same angle with respect to the normal to the mirror surface and in the same plane as the radiating source.
The second photo-detector, the "SCATTERED" is positioned on the lateral surface of Snell's cone to receive only a small portion ("background level") of the reflected radiation(figure 3).

When the instrument is turned on, the mirror is dry and clean, and the "DIRECT" photo-detector receives a great deal of radiation while the "SCATTERED" receives only the "BACKGROUND" level. As the Thermo-electric cooler removes heat from the mirror, the mirror surface temperature drops and a layer of condensate coalesces on the surface. The incident radiation is scattered, the "DIRECT" detector receives less light, and the "SCATTERED" detector receives more(figure 4).

However, when the mirror has particulate contaminants both the "DIRECT" and "SCATTERED" photo-detectors receive less light.

As is apparent from the previous discussion, the effect of Dew/Frost on the output of the photo-detectors is DIFFERENTIAL MODE while the effect of particulate contaminants is COMMON MODE(figure 4).

Temperature has a very large effect on the characteristics of the photo-detectors. The "DARK" current of photo-detectors for instance doubles every 20°C. By matching the type of photo-detectors and keeping them at the same temperature the "DARK" currents variations manifest themselves as COMMON MODE SIGNALS, and hence their effect can be canceled electronically. The emissivity of the radiation source is also very temperature sensitive. Once again, its variations are COMMON MODE and are nulled by the electronic circuitry.

The technique hence uses the differential model signal between photo-detectors to command the Thermo-electric cooler servo circuitry to stabilize the mirror temperature at the Dew/Frost temperature. It also uses the common mode signal to command a secondary servo loop (a regular) to accommodate for the presence of particulate contaminants or any other variation in the Electro- optic/mirror system(figure 5).

Furthermore, when the common mode signal into the secondary servo control exceeds a predetermined maximum value, the circuitry signals that it is no longer possible to electronically cancel the errors and that operator action is required.

CONCLUSION

The need for more accurate humidity measurement has been growing steadily for the past few years. The reason being a better understanding of the role played by humidity in processes as well as Meteorology and the associated need for high-performance/low-maintenance instruments.

The prices of OCM Hygrometers have traditionally been higher than the prices of systems using other technologies. As most users are aware, purchasing price is only a fraction of the total cost. Maintenance, re-calibration, and sensor replacement account for the balance. It is therefore important for users to realize that:

1. with OCM Hygrometers incorporating the sensing scheme described in this paper, preventive maintenance has virtually been eliminated.
2. with OCM Hygrometers there IS NO RECALIBRATION REQUIRED (physically cleaning a mirror does not affect calibration adjustments); and
3. the useful life of an OCM Hygrometer sensor (operated according to the manufacturer's specifications) is very long because it is passive and inert.

Figure 1

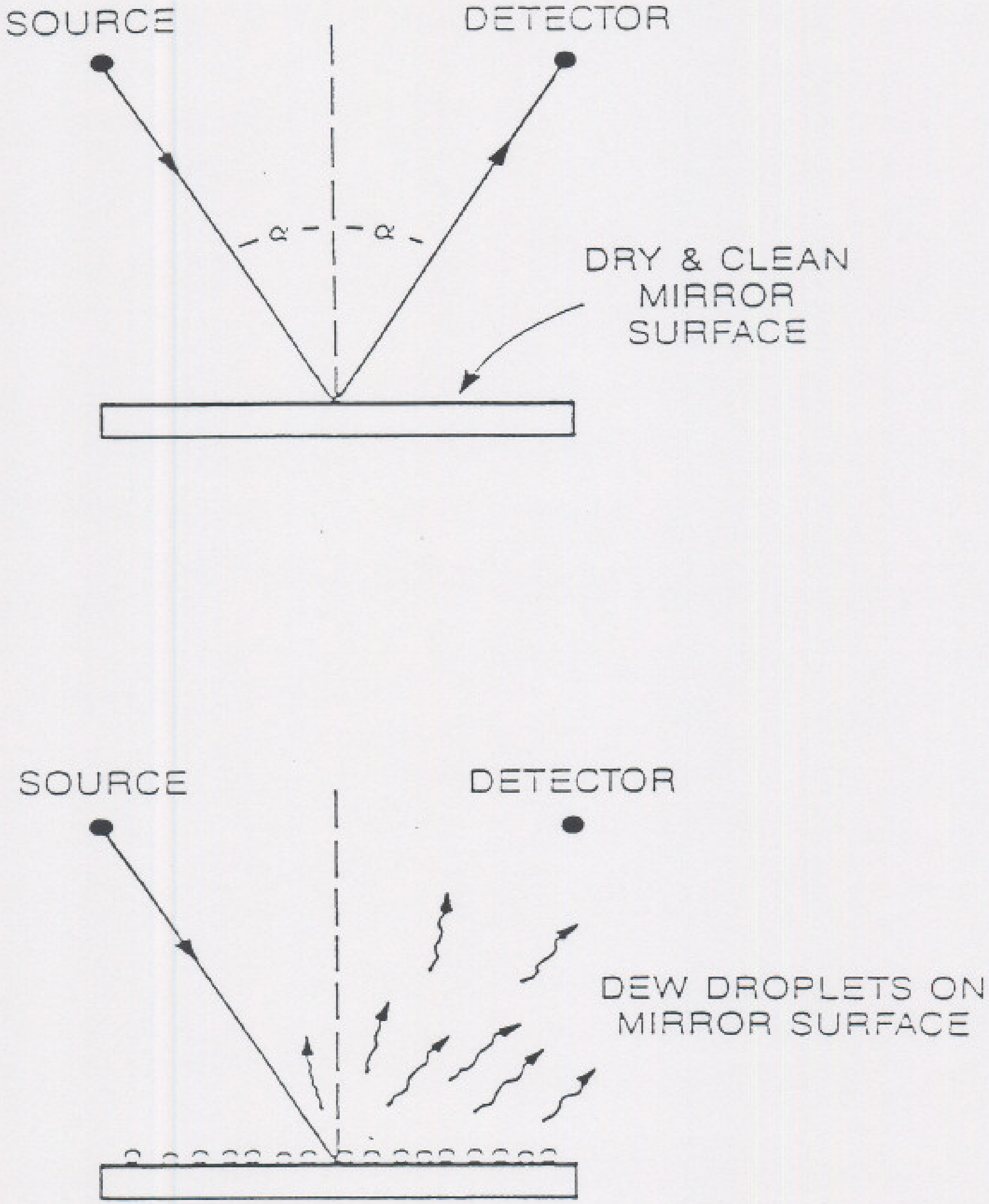

SOURCE
DETECTOR
α
α
DRY & CLEAN
MIRROR
SURFACE
SOURCE
DETECTOR
DEW DROPLETS ON
MIRROR SURFACE

Figure 2

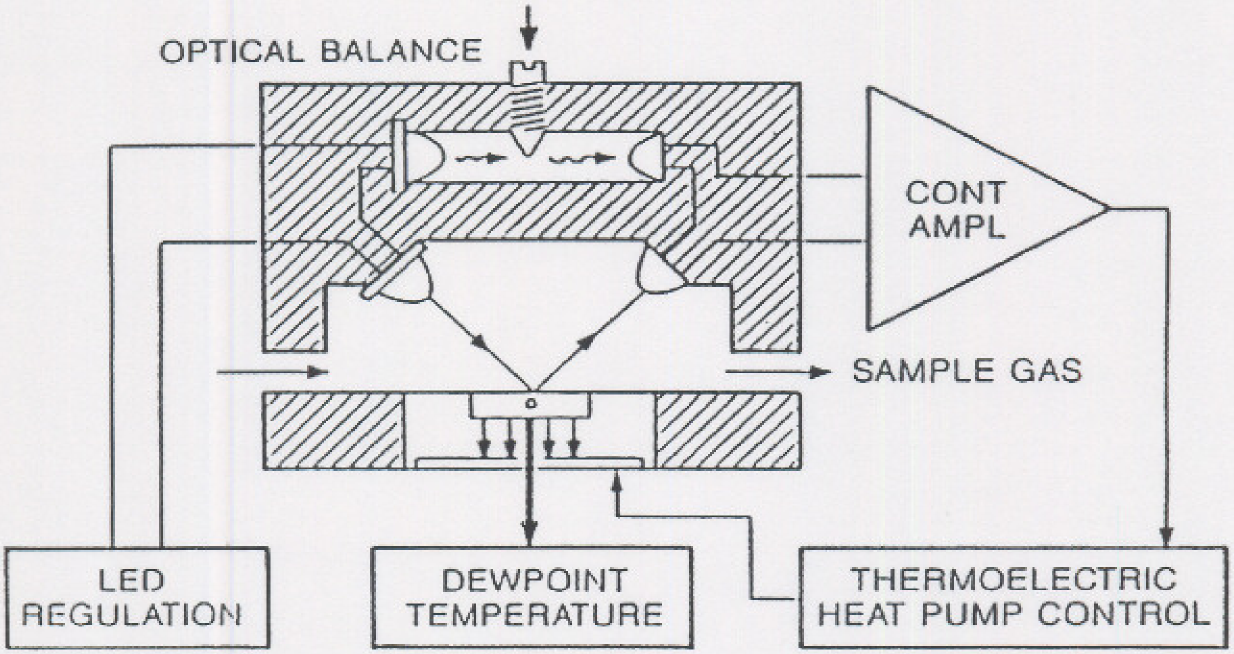

OPTICAL BALANCE
CONT AMPL
SAMPLE GAS
LED REGULATION
DEWPOINT TEMPERATURE
THERMOELECTRIC HEAT PUMP CONTROL

Figure 3

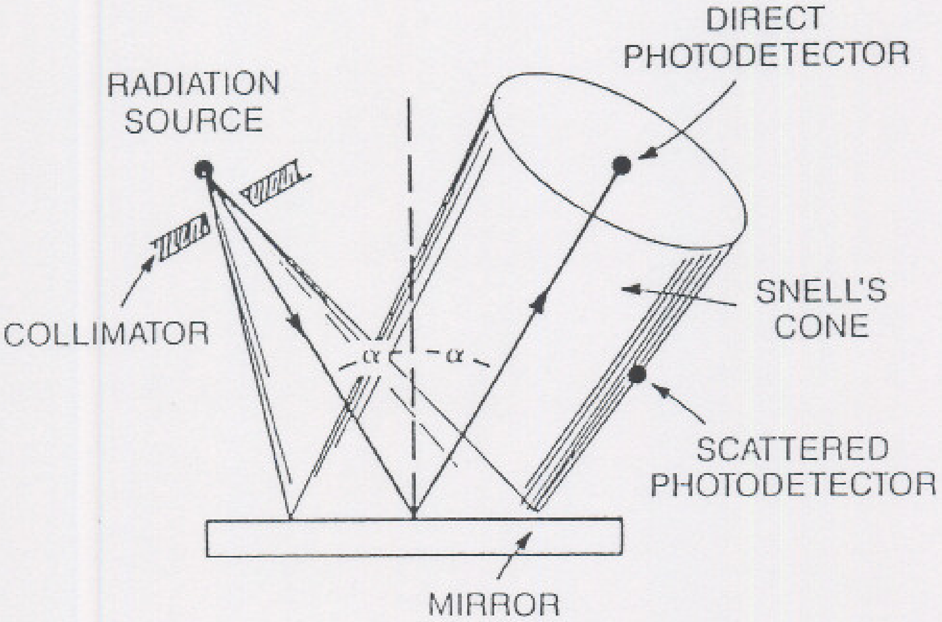

DIRECT PHOTODETECTOR
RADIATION SOURCE
COLLIMATOR
α
α
SNELL'S CONE
SCATTERED PHOTODETECTOR
MIRROR

Figure 4

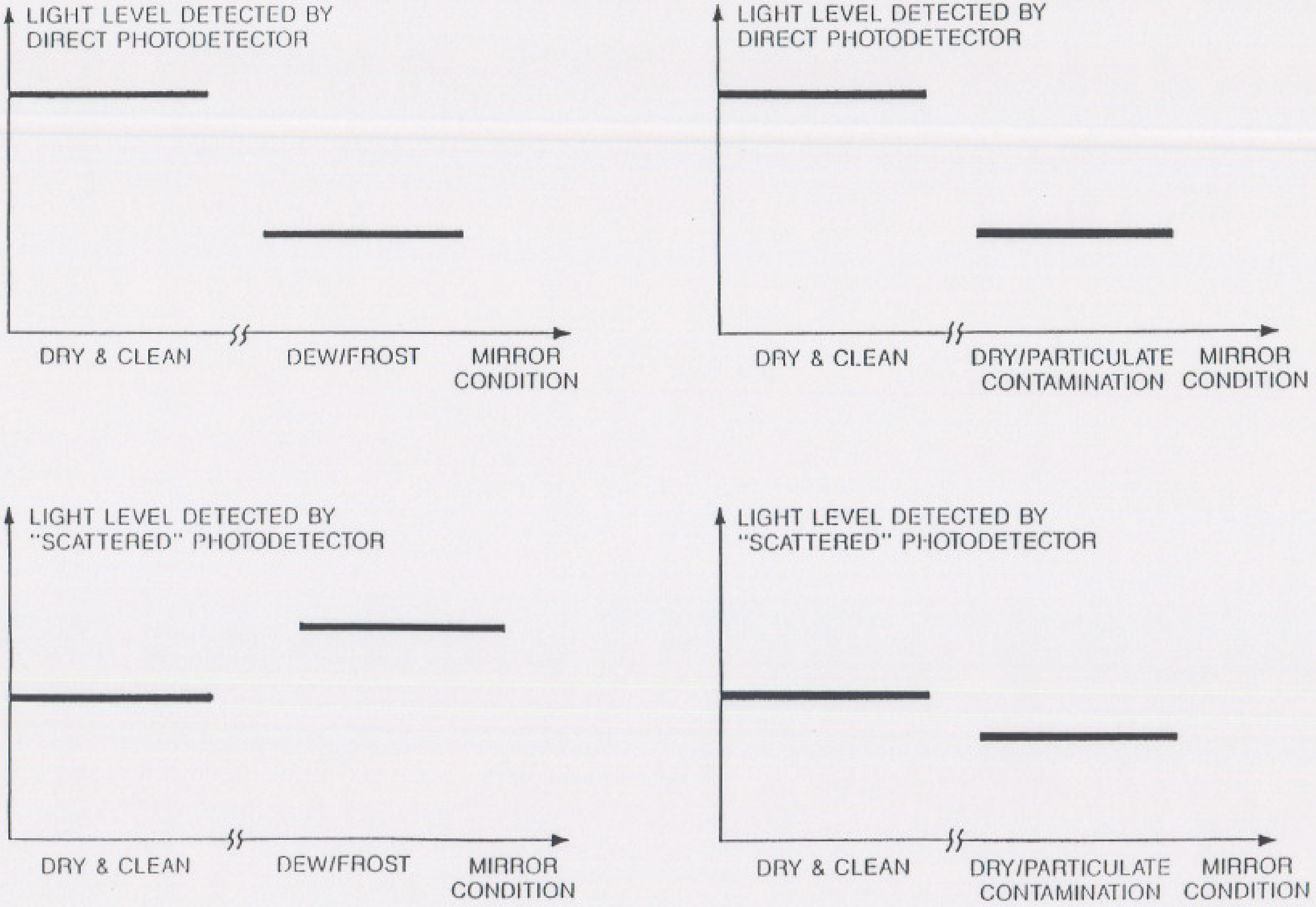
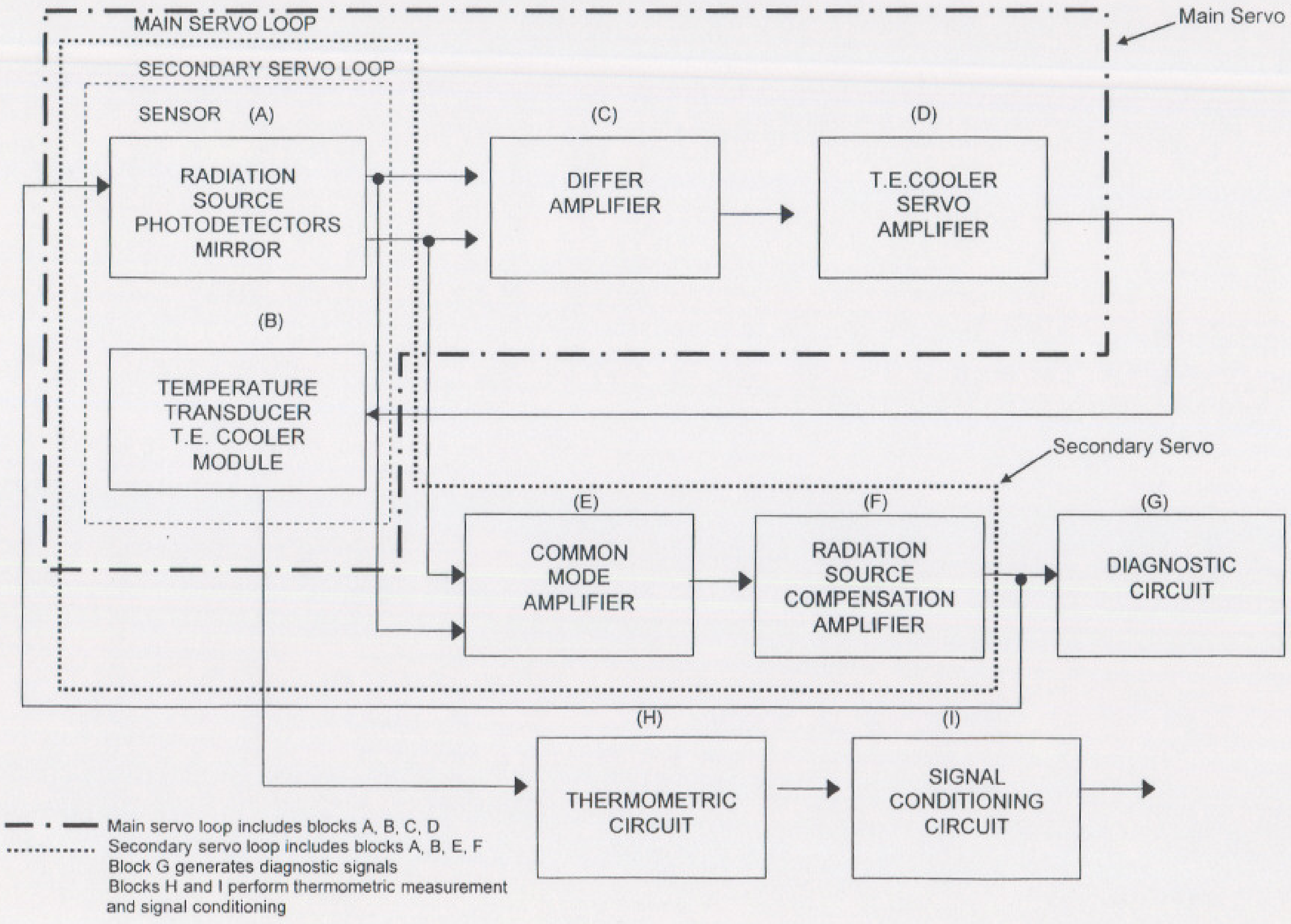

LIGHT LEVEL DETECTED BY
DIRECT PHOTODETECTOR
DRY & CLEAN
DEW/FROST
MIRROR CONDITION
LIGHT LEVEL DETECTED BY
DIRECT PHOTODETECTOR
DRY & CLEAN
DRY/PARTICULATE CONTAMINATION
MIRROR CONDITION
LIGHT LEVEL DETECTED BY
"SCATTERED" PHOTODETECTOR
DRY & CLEAN
DEW/FROST
MIRROR CONDITION
LIGHT LEVEL DETECTED BY
"SCATTERED" PHOTODETECTOR
DRY & CLEAN
DRY/PARTICULATE CONTAMINATION
MIRROR CONDITION

Figure 5

NEW SENSING SCHEME BLOCK DIAGRAM



— · — Main servo loop includes blocks A, B, C, D

.... Secondary servo loop includes blocks A, B, E, F

Block G generates diagnostic signals

Blocks H and I perform thermometric measurement and signal conditioning