High Sierra Electronics

Model 5790 Pyranometer
Instruction Manual 60-5790-01(B)

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1.0 INTRODUCTION

1.1 General Description:

The Model 5790-00 Pyranometer Sensor is designed for field measurements of solar radiation in energy, agricultural, meteorological, and hydrological applications. It has been used extensively in solar energy studies for site evaluation and monitoring passive system analysis, irrigation scheduling, and other environmental studies.

The 5790-00 features a silicon photovoltaic detector mounted in a fully cosine-corrected miniature head. It can be mounted in any plane, or hand held without affecting its performance.

For clear, unobstructed daylight conditions, the Model 5790-00 compares favorably with thermopile type pyranometers.

The pyranometer's spectral response does not cover the full range of the solar spectrum, but the error induced is less ±5% under most conditions of natural light. It is recommended the 5790-00 should not be used under vegetation or artificial lights because it has been calibrated for the daylight spectrum.

1.2 Receiving, Inspection and Unpacking:

The Model 5790 is a scientific instrument. Exercise care during unpacking and installation. Remove the contents of the package carefully and compare the contents with the enclosed packing list. Should any items be missing, notify *High Sierra Electronics* Customer Service. Please have your packing list available when you call.

If any of the items are received in damaged condition, immediately notify the carrier and request an inspection. You must notify the carrier within 15 days of shipment. If a claim is not made within that time period, then the carrier will not acknowledge any claim for the lost or damaged goods.

1.3 Specifications:

Accuracy	±5% in natural daylight conditions
Sensitivity	Typically 90µA per 1000 W/m²
Linearity	Max deviation of 1% up to 3000 W/m²
Stability	< +2% change over a 1 year period
Response time	10 µS
Cosine Correction	Cosine corrected up to 80° angle of incidence
Azimuth	<±1% error over 360° at 45° elevation
Tilt	No error induced from orientation
Operating Temperature	-40°C. to 65°C.
Relative Humidity	0 to 100%
Detector	High stability silicon photovoltaic detector
Sensor Housing	Weatherproof anodized aluminum case with acrylic diffuser and stainless steel hardware
Cable Length	50 Feet
Size (with leveling plate)	3″ (dia.) x 1 ½″ (H)
Model 4005 Signal Conditioning	
Power required	9 - 30 VDC @ <6mA below 1500 W/m²
Output	0 - 5 VDC
Calibration	5V @ 1500 W/m²
Size	¾″ (W) x 3 ½″ (L) x 2 ¼″ (H)
Mounting	Din Rail
Weight	1 Pound
Shipping Weight	2 Pounds

2.0 INSTALLATION

Before heading out to the field to install the Pyranometer it is best to verify that all components are operating per specifications. This sensor is best tested with direct sunlight. It is best to perform this test with the equipment that is to be used for the installation. If the site equipment is not available for testing, similar equipment may be used. A digital voltmeter and a battery with clip leads may also be used to test the operation of this sensor[1].

The following instructions are for sensor mounting at a site where there is already a standpipe or other equipment housing structure in place. Refer to system and sensor specific installation instructions for new installations.

The instructions that follow are for mounting the pyranometer using the *HSE* mounting arm (Model 5790-02) on a standpipe assembly.

It is best to choose mounting location clear of overhanging vegetation. The sensor should be mounted to minimize shading from the standpipe, antenna or mast assembly.

Mount the 5790-02 mounting arm on the antenna mast at the desired elevation with the two hose bands provided. Be certain that the mounting arm does not overhang a tipping bucket assembly (if used).

Mount the sensor on the leveling plate[2] on the mounting arm and feed the signal cable through the mast and into the standpipe. Adjust the leveling plate so that the level bubble is in the center of the bullseye.

Connect the signal cable to the signal conditioning circuit per the wire diagram in appendix 8.1

Connect the signal cable from the signal conditioning board to the Model 3200 series ALERT Data Transmitter.

Power the transmitter and check to see that the sensor is reporting a value consistent with solar conditions at the installation site. Shade the sensor and observe a change in sensor output consistent with the shaded condition.

With the cable ties provided, secure the sensor cable to the mounting arm and to the mast as necessary for a secure attachment. If multiple sensor cables share the same path, it is best to bundle those cables when securing them to the mast.

After mounting and testing all other sensors for the site, test all of the sensors before securing the site.

Once it is known that all equipment is operating as expected, return the transmitter to the standpipe hang the signal conditioning circuit board on the mounting plate in the standpipe and replace the top section and/or secure the door of the standpipe.

3.0 OPERATION

When connected to the Model 3200 series ALERT Data Transmitter, the operation of the sensor is automatic. The transmitter may be set to report on either a timed or an event report. It is recommended that if multiple analog sensors are

[1] See the wire diagram in Appendix 8.1 to determine how to wire the sensor signal conditioning circuit to the battery for this test.

[2] If a Model 5790-02 mounting arm was ordered with the pyranometer, the leveling plate is mounted on the mounting arm prior to shipping.

connected to a Model 3200 series ALERT Data Transmitter, the transmitter be set to report on a timed interval rather than an event report[3].

4.0 MAINTENANCE

During routine site service the only maintenance necessary is to clean the sensor, check to see that the it is level, and check that the signal cable is secure and has not been damaged. Remove any vegetation that has grown since the previous site visit that might be expected to interfere with sensor operation.

5.0 TROUBLESHOOTING

It should be noted that the majority of all failures are due to bad connections. Check all connectors.

Measure the battery voltage of the unit that is providing power to the sensor. Replace the battery if indicated.

Check that all wires are in the proper screw terminal and that the screws are tight. Where multiple wires enter the same screw terminal check each wire.

Check that the MS connector on the signal cable is fastened properly to the transmitter port to which it is connected.

Check that there is power getting to the signal conditioning circuit board and that there is an output signal being returned. Note that this unit is powered intermittently, so the *Test* button on the transmitter must be pushed while checking power or signal voltages.

If there are multiple sensors connected to the transmitter, disconnect all other sensors and test the pyranometer sensor alone. If the sensor works properly on its own, connect other sensors one at a time to determine which sensor may be causing the pyranometer sensor to give erroneous reports.

For technical assistance with this product, consult *High Sierra Electronics* technical personnel. Phone: 1-800-275 2080 or FAX: 1-530-273-2089 between 8:00 AM and 5:00 PM Pacific Coast time, Monday thru Friday. E-mail questions and comments to: service@highsierraelectonics.com.

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[3] If event reporting is desired for this sensor or any other analog sensor in use at the site, it is recommended that a *Model 3212 ALERT Data Transmitter* be specified on order. The Model 3212 ALERT Data Transmitter is fully programmable and each sensor may be individually programmed to report on either a timed interval, an event or both timed and event.

6.0 RETURNS

If you need to return this product for any reason, call *High Sierra Electronics* at (530) 273-2080 between 8:00 a.m. and 4:00 p.m. Pacific Coast time. Ask for a return Authorization Number (RA#) to be assigned to your unit. Carefully pack the unit so that it will not be further damaged in shipment. Write the RA# on the outside of the box and on any paperwork enclosed with the unit. Please include a written description of the problem and any unique conditions that occurred when the unit failed.

7.0 WARRANTY

All *High Sierra Electronics'* manufactured products are warranted against defects in materials and workmanship for a period of three (3) years from the date of shipment. If the equipment fails due to such defects, *High Sierra Electronics* will, as its option, repair or provide a replacement for the defective part or product. In no case will *High Sierra Electronics* be liable for more than the original purchase price.

Equipment supplied by *High Sierra Electronics* and manufactured by others, carries the respective manufacturer's warranty. *High Sierra Electronics* assumes no warranty obligation, either express or implied, for equipment manufactured by others and supplied by *High Sierra Electronics*.

THIS WARRANTY IS IN LIEU OF ALL OTHER WARRANTIES, EXPRESSED OR IMPLIED, INCLUDING, WITHOUT LIMITATION, ANY IMPLIED WARRANTY OF MERCHANT ABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ALL OF WHICH IS EXPRESSLY DISCLAIMED.

High Sierra Electronics Inc.
155 Spring Hill Dr. Suite 106
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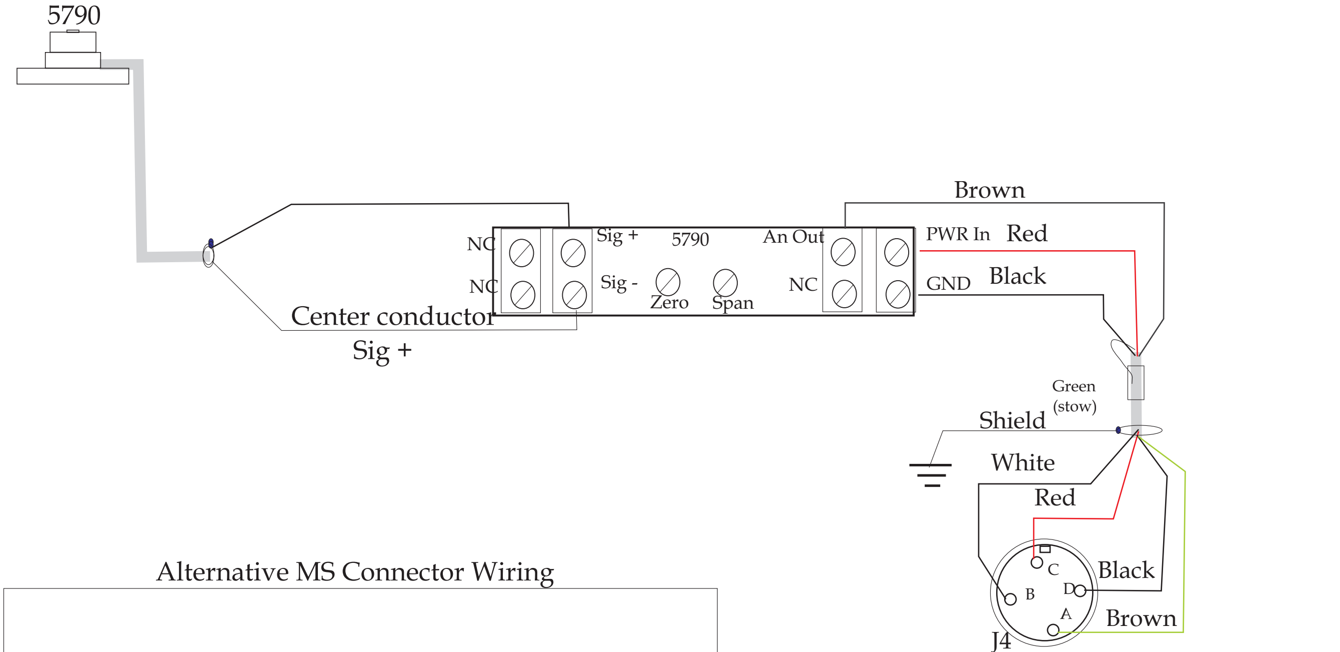
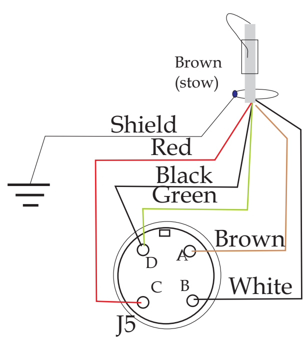


PH: J4

Pin	ID	Span	signal
A	ID +3	1500 W/SqM	0-5VDC

If desired the sensor signal may be transmitted on ID +4. The White wire (Pin B) stowed under the shrink tube should be connected to the signal output and the Brown wire stowed.

Alternative MS Connector Wiring

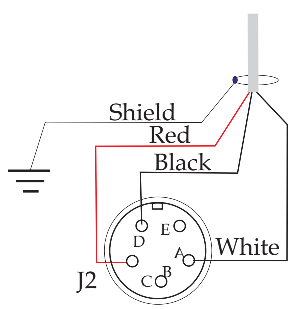


Alternate MS Connector wiring

PH: J5

Pin	ID	Span	signal
B	ID +2	1500 W/SqM	0-5VDC

The sensor signal may be transmitted on ID +1
The Brown wire (Pin A) stowed under the shrink tube should be connected to the signal output and the White wire stowed.



Pyranometer: J2

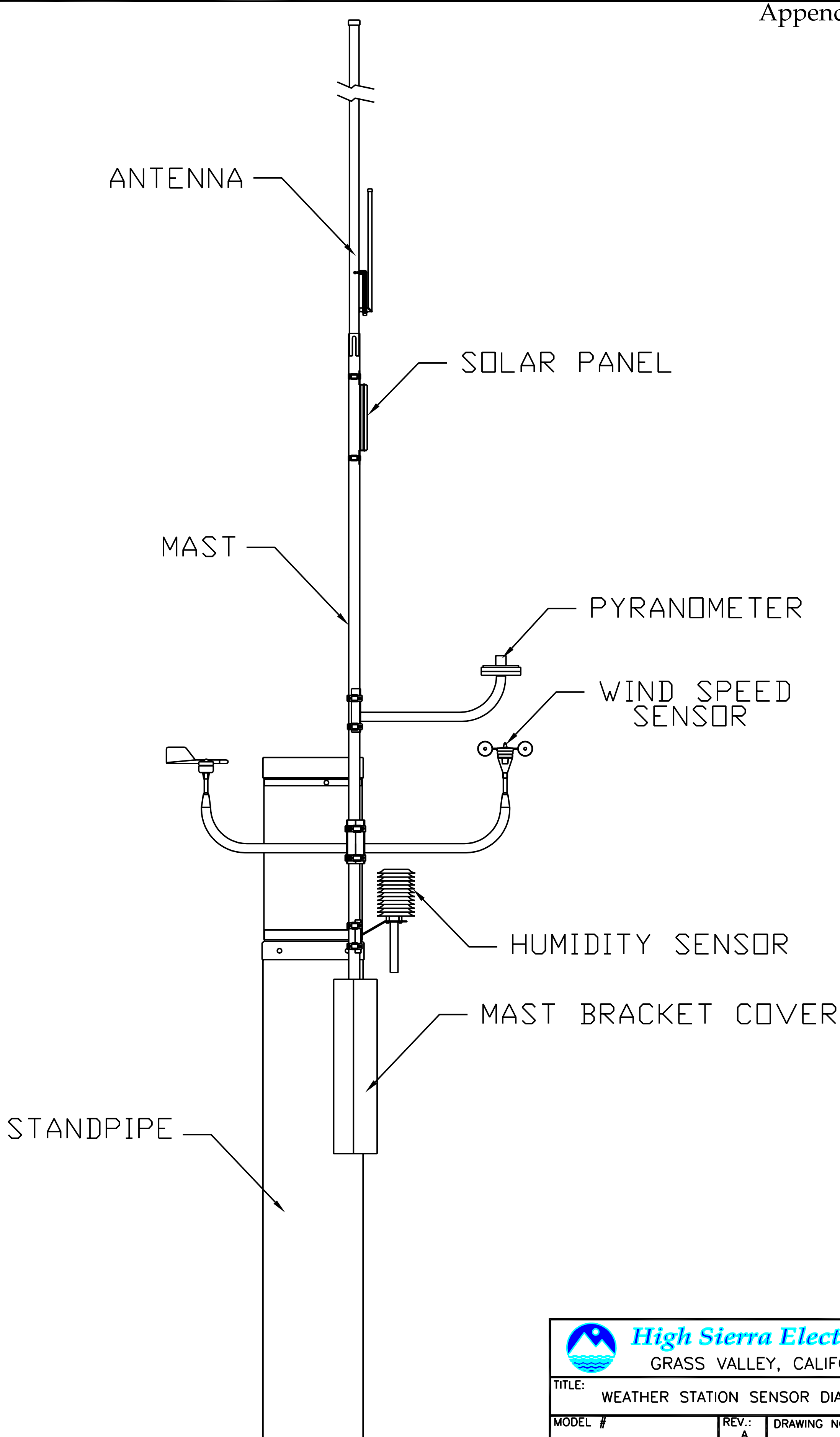
Pin	ID	Span	signal
A	ID+6	0-1500 W/SqM	0-5VDC

Available on Model 3206-10 Only

High Sierra Electronics
155 Spring Hill Drive, Grass Valley CA 95945
Phone: (530) 273-2080 Fax: (530) 273-2089

TITLE: Pyranometer Wire Diagram

MODEL NO.:	DRAWING NO.:	REV.:	APPROVED BY:
5790	61-5790-81	A	JS
DATE: 2/21, 2007		DRAWN BY: JAB	
FILE NAME: 61-5790-8x.cdr		SHEET Pyranometer	DO NOT SCALE



High Sierra Electronics GRASS VALLEY, CALIFORNIA			
TITLE: WEATHER STATION SENSOR DIAGRAM			
MODEL #	REV.: A	DRAWING NO.: 61-3451	
DRAWN BY: NAE	DATE: 03-20-07		
SIZE: B	SCALE: NONE	APPROVED BY:	SHT. NO.:

LI-200SA PYRANOMETER SENSOR

LI-COR, Inc. Toll Free: 1-800-447-3576 (U.S. & Canada) • Phone: 402-467-3576 • FAX: 402-467-2819 • E-mail: envsales@env.licor.com • Internet: http://www.licor.com

TOTAL SOLAR RADIATION

The LI-200SA Pyranometer is designed for field measurement of global solar radiation in agricultural, meteorological, and solar energy studies. In clear unobstructed daylight conditions, the LI-COR pyranometer compares favorably with first class thermopile type pyranometers (1, 2), but is priced at a fraction of the cost.

Patterned after the work of Kerr, Thurtell and Tanner (3), the LI-200SA features a silicon photovoltaic detector mounted in a fully cosine-corrected miniature head. Current output, which is directly proportional to solar radiation, is calibrated against an Eppley Precision Spectral Pyranometer (PSP) under natural daylight conditions in units of watts per square meter (w m^{-2}). Under most conditions of natural daylight, the error is <5%.

The spectral response of the LI-200SA does not include the entire solar spectrum (Figure 1), so it must be used in the same lighting conditions as those under which it was calibrated. Therefore, the LI-200SA should only be used to measure unobstructed daylight. It should NOT be used under vegetation, artificial lights, in a greenhouse, or for reflected solar radiation.

LI-200SA Pyranometer Sensor

LI-200SA SPECIFICATIONS

Calibration: Calibrated against an Eppley Precision Spectral Pyranometer (PSP) under natural daylight conditions. Typical error under these conditions is ± 5%.

Sensitivity: Typically 90 µA per 1000 W m^{-2}.

Linearity: Maximum deviation of 1% up to 3000 W m^{-2}.

Stability: < ± 2% change over a 1 year period.

Response Time: 10 µs.

Temperature Dependence: 0.15% per °C maximum.

Cosine Correction: Cosine corrected up to 80° angle of incidence.

Azimuth: < ± 1% error over 360° at 45° elevation.

Tilt: No error induced from orientation.

Operating Temperature: -40 to 65°C.

Relative Humidity: 0 to 100%.

Detector: High stability silicon photovoltaic detector (blue enhanced).

Sensor Housing: Weatherproof anodized aluminum case with acrylic diffuser and stainless steel hardware.

Size: 2.38 Dia. × 2.54 cm H (0.94" × 1.0").

Weight: 28 g (1 oz).

Cable Length: 3.0 m (10 ft).

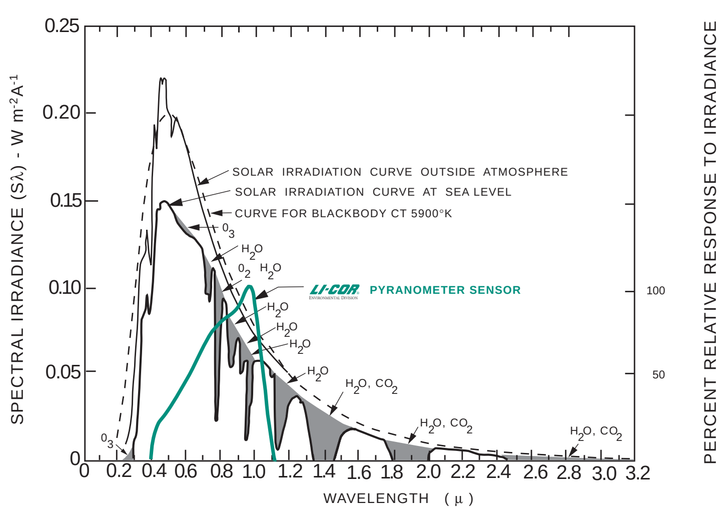


Figure 1. The LI-200SA Pyranometer spectral response is illustrated along with the energy distribution in the solar spectrum (3).

ORDERING INFORMATION

The LI-200SA Pyranometer Sensor cable terminates with a BNC connector that connects directly to the LI-250 Light Meter or LI-1400 DataLogger. The 2220 Millivolt Adapter should be ordered if the LI-200SA will be used with a strip chart recorder or datalogger that measures millivolts. The 2220 uses a 147 ohm precision resistor to convert the LI-200SA output from microamps to millivolts. The sensor can also be ordered with bare leads (without the connector) designated LI-200SZ. Both are available with 50 foot cables, LI-200SA-50 or LI-200SZ-50. The 2003S Mounting and Leveling Fixture is recommended for each sensor unless other provisions for mounting are made. Other accessories are described on the Accessory Sheet.

LI-200SA Pyranometer
LI-200SZ Pyranometer
LI-200SA-50 Pyranometer
LI-200SZ-50 Pyranometer
2220 Millivolt Adapter
2003S Mounting and Leveling Fixture
2222SB-50 Extension Cable
2222SB-100 Extension Cable

REFERENCES

1. Flowers, E.C. 1978. Comparison of solar radiation sensors from various manufacturers. In: 1978 annual report from NOAA to the DOE.

2. Palmiter, L.S., L.B. Hamilton, M.J. Holtz. 1979. Low cost performance evaluation of passive solar buildings. SERI/RR-63-223. UC-59B.

3. Kerr, J.P., G.W. Thurtell and C.B. Tanner. 1967. An integrating pyranometer for climatological observer stations and mesoscale networks. J. Appl. Meterol. 6:688-694.

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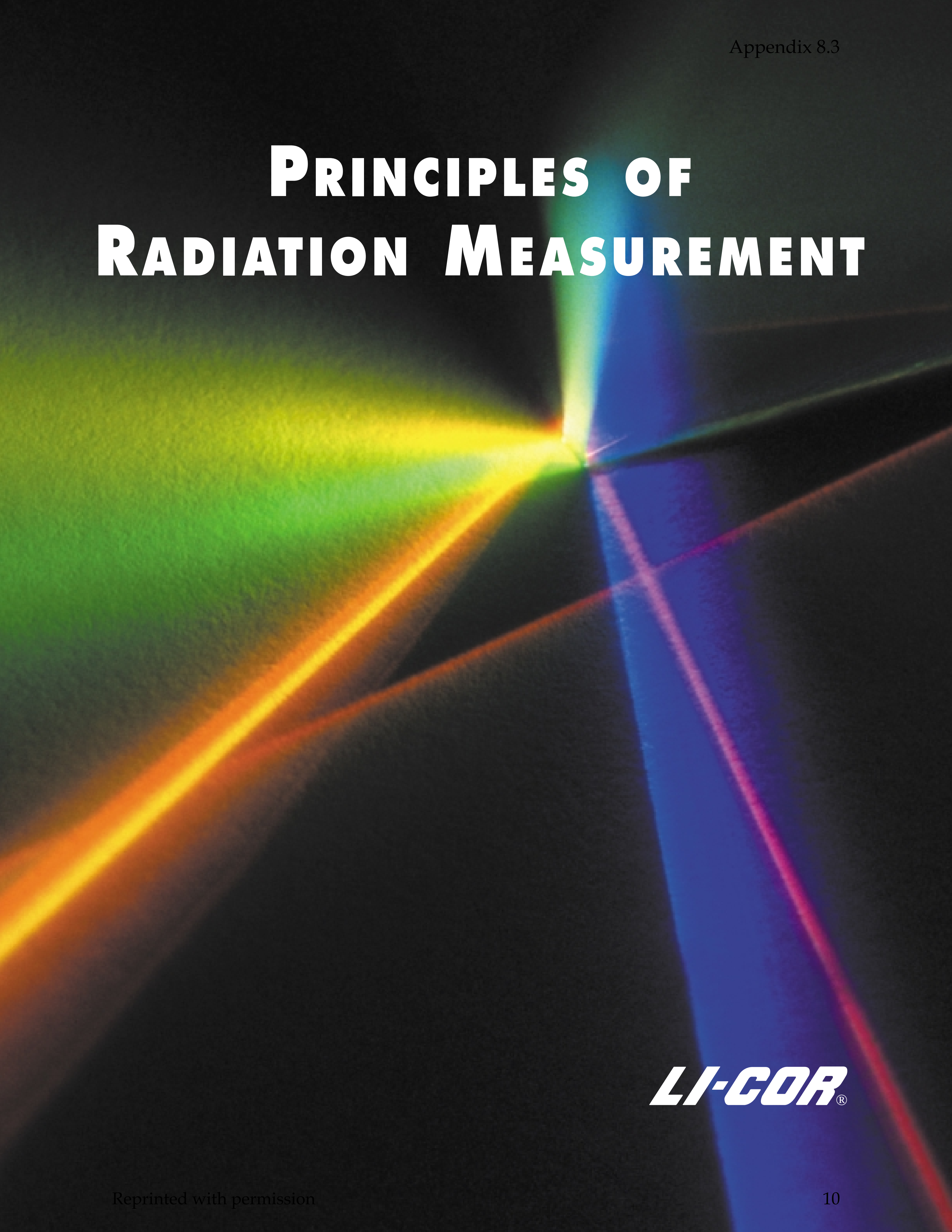
PRINCIPLES OF RADIATION MEASUREMENT



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Radiation Measurement

Much confusion has existed regarding the measurement of radiation. This report presents a comprehensive summary of the terminology and units used in radiometry, photometry, and the measurement of photosynthetically active radiation (PAR). Measurement errors can arise from a number of sources, and these are explained in detail. Finally, the conversion of radiometric and photometric units to photon units is discussed. In this report, the International System of Units (SI) is used unless noted otherwise (9).

RADIOMETRY

Radiometry (1) is the measurement of the properties of radiant energy (SI unit: joule, J), which is one of the many interchangeable forms of energy. The rate of flow of radiant energy, in the form of an electromagnetic wave, is called the radiant flux (unit: watt, W; 1 W = 1 J s^{-1}) Radiant flux can be measured as it flows from the source (the sun, in natural conditions), through one or more reflecting, absorbing, scattering and transmitting media (the Earth's atmosphere, a plant canopy) to the receiving surface of interest (a photosynthesizing leaf) (8).

Terminology and Units

Radiant Flux is the amount of radiation coming from a source per unit time. Unit: watt, W.

Radiant Intensity is the radiant flux leaving a point on the source, per unit solid angle of space surrounding the point. Unit: watts per steridian, W sr^{-1}.

Radiance is the radiant flux emitted by a unit area of a source or scattered by a unit area of a surface. Unit: W m^{-2} sr^{-1}.

Irradiance is the radiant flux incident on a receiving surface from all directions, per unit area of surface. Unit: W m^{-2}.

Absorptance is the fraction of the incident flux that is absorbed by a medium.

Reflectance and Transmittance are equivalent terms for the fractions that are reflected or transmitted.

Spectroradiometry: All the properties of the radiant flux depend on the wavelength of the radiation. The prefix spectral is added when the wavelength dependency is being described. Thus, the spectral irradiance is the irradiance at a given wavelength, per unit wavelength interval. The irradiance within a given waveband is the integral of the spectral irradiance with respect to wavelength (8). Unit: W m^{-2} nm^{-1} . Spectral measurements can be made using the LI-1800 Portable Spectroradiometer. Global solar radiation is the solar irradiance received on a horizontal surface (also referred to as the direct component of sunlight plus the diffuse component of skylight received together on a horizontal surface). This physical quantity is measured by a pyranometer such as the LI-200SA. Unit: W m^{-2}.

Direct Solar Radiation is the radiation emitted from the solid angle of the sun's disc, received on a surface perpendicular to the axis of this cone, comprising mainly unscattered and unreflected solar radiation. This physical quantity is measured by a pyrheliometer. Unit: W m^{-2}.

Diffuse Solar Radiation (sky radiation) is the downward scattered and reflected radiation coming from the whole hemisphere, with the exception of the solid angle subtended by the sun's disc. Diffuse radiation can be measured by a pyranometer mounted on a shadow band, or calculated using global solar radiation and direct solar radiation. Unit: W m^{-2}.

PHOTOSYNTHETICALLY ACTIVE RADIATION

In the past there has been disagreement concerning units and terminology used in radiation measurements in conjunction with the plant sciences. It is LI-COR's policy to adopt the recommendations of the international committees, such as the Commission Internationale de I'Eclairage (CIE), the International Bureau of Weights and Measures, and the International Committee on Radiation Units. The International System of Units (SI) should be used wherever a suitable unit exists (9).

Units

The SI unit of radiant energy flux is the watt (W). There is no official SI unit of photon flux. A mole of photons is commonly used to designate Avogadro's number of photons (6.022×10^{23} photons). The einstein has been used in the past in plant science, however, most societies now recommend the use of the mole since the mole is an SI unit. When either of these definitions is used, the quantity of photons in a mole is equal to the quantity of photons in an einstein (1 mole = 1 einstein = 6.022×10^{23} photons). Note: The einstein has also been used in books on photochemistry, photobiology and radiation physics as the quantity of radiant energy in Avogadro's number of photons (5). This definition is not used in photosynthesis studies.

Terminology

LI-COR continues to follow the lead of the Crop Science Society of America, Committee on Terminology (10) and other societies (11) until international committees put forth further recommendations.

Photosynthetically Active Radiation (PAR) is defined as radiation in the 400 to 700 nm waveband. PAR is the general radiation term which covers both photon terms (7) and energy terms.

Photosynthetic Photon Flux Density (PPFD) is defined as the photon flux density of PAR, also referred to as Quantum Flux Density. This is the number of photons in the 400-700 nm waveband incident per unit time on a unit surface. The ideal PPFD sensor responds equally to all photons in the 400-700 nm waveband and has a cosine response. This physical quantity is measured by a cosine (180˚) quantum sensor such as the LI-190SA or LI-192SA. The LI-191SA Line Quantum Sensor also measures PPFD. Figure 1 shows an ideal quantum response curve and the typical spectral response curve of LI-COR quantum sensors.
Units: 1 µmol s^{1} m^{-2} ≡ 1 µE s^{1} m^{-2} ≡ 6.022 • 10^{17} photons s^{-1} m^{-2}.

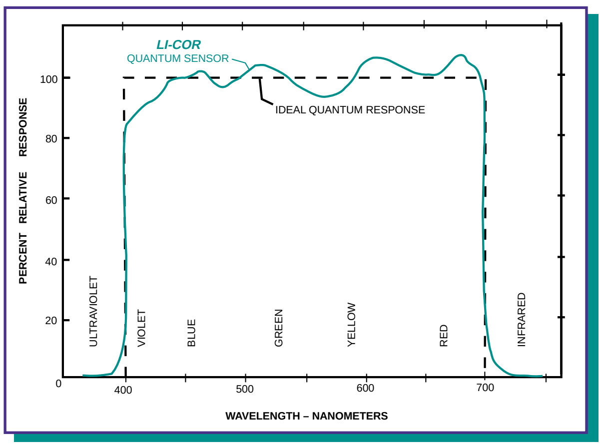

Figure 1. Typical spectral response of LI-COR Quantum Sensors and a photosynthetic irradiance sensor vs. wavelength and ideal quantum response.

Photosynthetic Photon Flux Fluence Rate (PPFFR) LI-COR introduced this term which is defined as the photon flux fluence rate of PAR, also referred to as Quantum Scaler Irradiance or Photon Spherical Irradiance. This is the integral of photon flux radiance at a point over all directions about the point. The ideal PPFFR sensor has a spherical collecting surface which exhibits the properties of a cosine receiver at every point on its surface (Figure 2) and responds equally to all photons in the 400-700 nm waveband (Figure 1). This physical quantity is measured by a spherical (4π collector) quantum sensor such as the LI-193SA. Units: 1 µmol s^{1} m^{-2} ≡ 1 µE s^{1} m^{-2} ≡ 6.022 × 10^{17} photons s^{-1} m^{-2} ≡ 6.022 • 10^{17} quanta s^{-1} m^{-2}.

Note: There is no unique relationship between the PPFD and the PPFFR. For a collimated beam at normal incidence, they are equal; while for perfectly diffuse radiation, the PPFFR is 4 times the PPFD. In practical situations the ratio will be somewhere between 1 and 4.

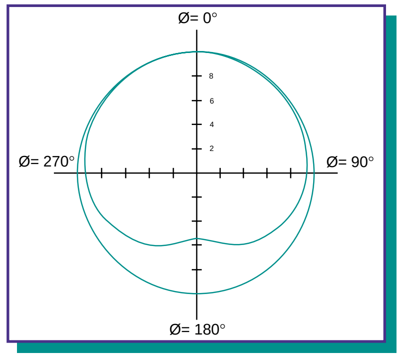

Figure 2. Typical Angular Response of the LI-193SB Spherical Quantum Sensor.

PHOTOMETRY

Photometry refers to the measurement of visible radiation (light) with a sensor having a spectral responsivity curve equal to the average human eye. Photometry is used to describe lighting conditions where the eye is the primary sensor, such as illumination of work areas, interior lighting, television screens, etc. Although photometric measurements have been used in the past in plant science, PPFD and irradiance are the preferred measurements. The use of the word "light" is inappropriate in plant research. The terms "ultraviolet light" and "infrared light" clearly are contradictory (8).

The spectral responsivity curve of the standard human eye at typical light levels is called the CIE Standard Observer Curve (photopic curve), and covers the waveband of 380-770 nm. The human eye responds differently to light of different colors and has maximum sensitivity to yellow and green (Figure 3). In order to make accurate photometric measurements of various colors of light or from differing types of light sources, a photometric sensor's spectral responsivity curve must match the CIE photopic curve very closely.

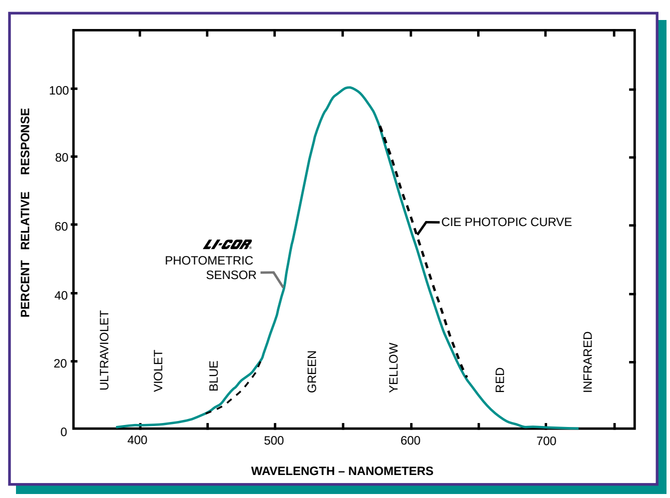

Figure 3. Typical spectral response of LI-COR Photometric Sensors vs. the CIE photopic response curve.

Terminology and Units (4)

Luminous Flux is the amount of radiation coming from a source per unit time, evaluated in terms of a standardized visual response. Unit: lumen, lm.

Luminous Intensity is the luminous flux per unit solid angle in the direction in question. Unit: candela, cd. One candela is one lm sr^{-1}.

Luminance is the quotient of the luminous flux at an element of the surface surrounding the point and propagated in directions defined by an elementary cone containing the given direction, by the product of the solid angle of the cone and the area of the orthogonal projection of the element of the surface on a plane perpendicular to the given direction. Unit: cd m^{-2}; also, lm sr^{-1} m^{-2}. This unit is also called the nit.

Illuminance is defined as the density of the luminous flux incident at a point on a surface. Average illuminance is the quotient of the luminous flux incident on a surface by the area of the surface. This physical quantity is measured by a cosine photometric sensor such as the LI-210SA.
Unit: lux, lx. One lux is one lm m^{-2}.

Measurement Errors

At a Controlled Environments Working Conference in Madison, Wisconsin, USA (1979), an official from the U.S. National Bureau of Standards (NBS) stated that one could not expect less than 10 to 25% error in radiation measurements made under non-ideal conditions. In order to clarify this area, the sources of errors which the researcher must be aware of when making radiation measurements have been tabulated. Refer also to the specifications given with each sensor for further details.

Absolute Calibration Error

Absolute calibration error depends on the source of the lamp standard and its estimated uncertainty at the time of calibration, accuracy of filament to sensor distance, alignment accuracy, stray light, and the lamp current measurement accuracy. Where it is necessary to use a transfer sensor (such as for solar calibrations) additional error will be introduced. LI-COR quantum and photometric sensors are calibrated against a working quartz halogen lamp. These working quartz halogen lamps have been calibrated against laboratory standards traceable to the NBS. Standard lamp current is metered to 0.035% accuracy. Microscope and laser alignment in the calibration setup reduce alignment errors to less than 0.1%. Stray light is reduced by black velvet to less than 0.1%. The absolute calibration accuracy is limited to the uncertainty of the NBS traceable standard lamp. The absolute calibration specification for LI-COR sensors is ±5% traceable to the NBS. This accuracy is conservatively stated and the error is typically ±3%. Absolute calibrations and spectral responses of LI-COR sensors have been checked by the National Research Council of Canada (NRC) to insure the accuracy and quality of LI-COR calibrations.

Relative Error (Spectral Response Error)

This error is also called actinity error or spectral correction error. This error is due to the spectral response of the sensor not conforming to the ideal spectral response. This error occurs when measuring radiation from any source which is spectrally different than the calibration source.

The quantum and photometric sensor spectral response conformity is checked by LI-COR using a monochromator and calibrated silicon photodiode. The spectral response of the sensor is achieved by the use of computer-tailored filter glass. Relative errors for various sources due to a non-ideal spectral response are checked by actual measurement and a computer program which utilizes the source spectral irradiance data and the sensor spectral response data.

The relative error specifications given for LI-COR quantum and photometric sensors are for use in growth chambers, daylight, greenhouses, plant canopies and aquatic conditions. When used with sources that have strong spectral lines such as gas lamps or lasers, this error could be larger depending on the location of the lines.

The LI-COR pyranometer measures irradiance from the sun plus sky. The LI-200SA is not spectrally ideal (equal spectral response from 280-2800 nm). See Figure 4. Therefore, it should be used only under natural, unobstructed daylight conditions. NOAA states in a test report that for clear, unobstructed daylight conditions, the LI-COR pyranometer compares very well with class one thermopile pyranometers (3). The LI-200SA is a WMO (World Meteorological Organization) class two pyranometer.

The LI-200SA should not be used under spectrally different radiation (than the sun), such as in growth chambers, greenhouses, and plant canopies. Under such artificial or shaded conditions, a thermopile pyranometer should be used.

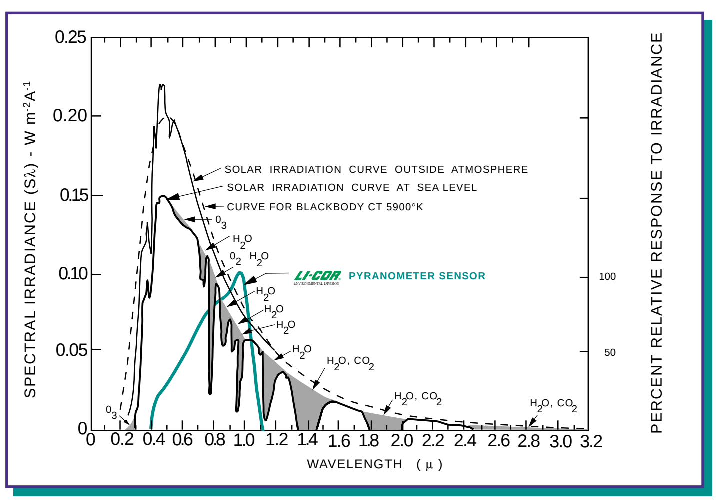

Figure 4. The LI-200SA Pyranometer spectral response is illustrated along with the energy distribution in the solar spectrum (5).

Spatial Error

This error is caused by a sensor not responding to radiation at various incident angles. Spatial error consists of the cosine error (or the angular error) and azimuth error.

Cosine Error

A sensor with a cosine response (follows Lambert's cosine law) allows measurement of flux densities through a given plane, i.e. flux densities per unit area. When a parallel beam of radiation of given cross-sectional area spreads over a flat surface, the area that it covers is inversely proportional to the cosine of the angle between the beam and a plane nor mal to the surface. Therefore, the irradiance due to the beam is proportional to the cosine of the angle. A radiometer, whose response to beams coming from different directions follows the same relationship, is said to be "cosine-corrected" (6). A sensor without an accurate cosine correction can give a severe error under diffuse radiation conditions within a plant canopy, at low solar elevation angles, under fluorescent lighting, etc.

Cosine response is measured by placing the sensor on a platform which can be adjusted to rotate the sensor about an axis placed across the center of the measuring surface. A collimated source is directed at normal incidence and the output of the sensor is measured as the angle of incidence is varied. The cosine error at angle 0 is the percent difference of the ratio of the measured output at angle 0 and normal incidence (angle 0°) as compared to the cosine of angle 0. This is repeated for various azimuth angles as necessary.

The LI-190SA, LI-200SA and LI-210SA are fully corrected cosine sensors. These sensors have a typical cosine error of less than 5% up to an 80° angle of incidence. Totally diffuse radiation introduces a cosine error of approximately 2.5%. For sun plus sky at a sun elevation of 30° (60° angle of incidence), the error is ≈2%. The LI-192SA sensor has a slightly greater cosine error since this sensor has a cosine response optimized for both air and water. The LI-191SA uses uncorrected acrylic diffusers and has a greater error at high angles of incidence. For totally diffuse radiation, the error is ≈8%. For conditions within canopies, the error is less because the radiation is not totally diffuse.

Angular Error

A spherical PPFFR sensor measures the total flux incidence on its spherical surface divided by the cross-sectional area of the sphere. Angular error is measured by directing a collimated source at normal incidence and rotating the sensor 360° about an axis directly through the center of the sphere at 90° from normal incidence. This is repeated for various azimuth angles as necessary to characterize the sensor.

The LI-193SA angular error is due to variations in density in the diffusion sphere and the sphere area lost because of the sensor base (Figure 2). This error is less than -10% for total because the upwelling radiation is much smaller than the downwelling radiation.

Azimuth Error

This is a subcategory of both cosine and angular error. It is specified separately at a particular angle of incidence. This error is the percent change of the sensor output as the sensor is rotated about the normal axis at a particular angle of incident radiation. This error is less than ±1% at 45° for the LI-190SA, LI-192SA, LI-200SA, and LI-210SA sensors. The error is less than ±3% for the LI-191SA and LI-193SA sensors.

Displacement Error

In highly turbid waters, the LI-193SA Spherical Sensor will indicate high PPFFR values due to the displacement of water by the sensor sphere volume. This is because the point of measurement is taken to be at the center of the sphere, but the attenuation which would have been provided by the water within the sphere is absent. This error is typically +6% for water with an attenuation coefficient of 3 m^{-1} (2).

Tilt Error

Tilt error exists when a sensor is sensitive to orientation due to the effects of gravity. This exists primarily in thermopile type detectors. Silicon type detectors do not have this error. All LI-COR sensors are of the latter type and have no tilt error. This error in the LI-200SA Pyranometer is nonexistent and has an advantage over thermopile type detectors for solar radiation measurements (3).

Linearity Error

Linearity error exists when a sensor is not able to follow proportionate changes in radiation. The type of silicon detectors used in LI-COR sensors have a linearity error of less than ±1% over seven decades of dynamic range.

Fatigue Error

Fatigue error exists when a sensor exhibits hysteresis. This is common in selenium-based illumination meters and can add a considerable error. For this reason, LI-COR sensors incorporate only silicon detectors which exhibit no fatigue error.

Temperature Coefficient Error

Temperature coefficient error exists when the output of a sensor changes with a constant input. This error is typically less than ±0.1% per °C for the LI-190SA, LI-191SA, LI-192SA, LI-193SA, and LI-210SB sensors. This error is slightly higher for the LI-200SA.

Response Time Error

This error exists when the source being measured changes rapidly during the period of measurement.

Averaging:

Large errors can exist when measuring radiation under rapidly changing conditions such as changing cloud cover and wind if measuring within a crop canopy, and waves if measuring underwater. The use of an integrating meter to average the reading will eliminate this error.

Instantaneous:

When radiation measurements are desired over a period of time (much less than the response time of the system), large errors can exist. For example, if one were to measure the radiation from a pulsed source (such as a gas discharge flash lamp) with a typical system designed for environmental measurements, the reading would be meaningless. Such a measurement should not be made with LI-COR instruments without consultation with LI-COR.

Long-Term Stability Error

This error exists when the calibration of a sensor changes with time. This error is usually low for sensors using high quality silicon photovoltaic photodiodes and glass filters. LI-COR uses only high quality components. The use of Wratten filters and/or inexpensive silicon or selenium cells add significantly to long-term stability error. The stability error of LI-COR sensors is typically ±2% per year.

Important: Customers should have their sensors recalibrated every two years.

Immersion Effect Error

A sensor with a diffuser for cosine correction will have an immersion effect when used under water. Radiation entering the diffuser scatters in all directions within the diffuser, with more radiation lost through the water-diffuser interface than in the case when the sensor is in the air. This is because the air-diffuser interface offers a greater ratio of indices of refraction than the water-diffuser interface. LI-COR provides a typical immersion effect correction factor for the underwater sensors. Immersion effect error is the difference between this typical figure and the actual figure for a given sensor in a particular environment. Since LI-COR test measurements are done in clear water, the error is also dependent on other variables such as turbidity, salinity, etc. Immersion effect error is typically ±2% or less. A complete report on the immersion effect properties of LI-COR underwater sensors is available from LI-COR.

Surface Variation Error

In general, the absolute responsivity and the relative spectral responsivity are not constant over the radiation-sensitive surface of sensors. This error has little effect in environmental measurements except for spatial averaging sensors such as the LI-191SA. This error is < ±7% for the LI-191SA.

User Errors

Spatial User Error

This is different than sensor-caused spatial error. Spatial user error can be introduced by using a single small sensor to characterize the radiation profile within a crop canopy or growth chamber. The flux density measured on a given plane can vary considerably due to shadows and sunflecks. To neglect this in measurements can introduce errors up to 1000%. Multiple sensors or sensors on track scanners can be used to minimize this error. If track scanners are used, the output of the sensors must be integrated.

The LI-191SA Line Quantum Sensor, which spatially averages radiation over its one meter length, minimizes this error and allows one person to easily make many measurements in a short period of time. Another method, although not as accurate, is to use an integrating meter and the LI-190SA quantum Sensor and physically scan the sensor by hand within the canopy while integrating the output with the meter.

Another type of spatial user error can be caused by misapplication of a cosine-corrected sensor where a spherical sensor would give a more accurate measurement. An example is in underwater photosynthetic radiation measurements when studying phytoplankton.

User Setup/Application Errors

These errors include such causes as:

- Reflections or obstructions from clothing, buildings, boats, etc.
- Dust, flyspecks, seaweeds, bird droppings, etc.
- Shock, causing permanent damage of optics within the sensor.
- Submersion of terrestrial sensors in water for an extended period (partial or total). Rain doesn't affect the sensors since they are completely weatherproof.
- Use of the incorrect calibration constant.
- Incorrect interpolation of analog meters.
- Using the wrong meter function.
- Failure to have sensors recalibrated periodically.

Readout Error

This error is due to the readout instrument as distinguished from the sensor. Zero drift, temperature, battery voltage, electronic stability, line voltage, humidity and shock are all factors which can contribute to readout error. The use of electronic circuitry such as chopper-stabilized amplifiers and voltage regulators in LI-COR meters largely eliminates many of these problems: zero drift, temperature, battery voltage, electronic stability, line voltage.

Total Error

The errors given are largely independent of each other and are random in polarity and magnitude. Therefore, they can be summed in quadrature (the square root of the sum of the squares). The total error is shown below for an LI-190SA Quantum Sensor and LI-COR meters when used for measuring lighting in a typical growth chamber or natural daylight over a temperature range of 15° to 35°C.

	Typical Error
Absolute Error	5% max., 3% typical
Relative (spectral response) Error	5%
Spatial (cosine) Error	2%
Displacement Error	0%
Tilt Error	0%
Linearity Error	0%
Fatigue Error	0%
Sensor Temperature Coefficient Error	1 % (0.1% per °C)
Response Time Error	0%
Long-term Stability Error	2% (2% per year)
Immersion Effect Error	0%
Surface Variation Error	0%
Readout Error	1%
User Error	?

The total error = Square Root $(5 \times 5 + 5 \times 5 + 2 \times 2 + 1 \times 1)$ = 7.6%. All of the above errors are minimized by LI-COR through design and calibration. While this error seems reasonably low, it must be remembered that no user error has been added, and that statistically it is possible that all the errors could be of the same polarity. The sum of the errors (less the user error) could equal 21% in the worst case. The absolute error is conservatively stated and is more typically ±3%. User error in vegetation canopies where shadows and sunflecks exist can be very large (1000%) and one of the methods described under Spatial User Error should be employed.

When purchasing a radiation measuring system, it is necessary to insure that the spatial (cosine, etc.) and relative spectral response errors are as low as possible. These two errors depend upon the skill and expertise of the designer and manufacturer. Some manufacturers deliberately do not give specifications for these errors and the user can expect large errors. The absolute error is largely dependent on the NBS lamp standard. Minimization of this error can be achieved by the more experienced companies through the use of precise techniques and expensive capital equipment. In order to insure long-term stability, it is necessary that the manufacturer use the highest quality silicon photovoltaic/photodiodes and only the best glass filters. Modern electronic readout instruments virtually eliminate readout error.

The user should be aware of all the types of errors that can occur, particularly the relative and spatial errors, since these can add considerably to the total error. LI-COR has and continues to put forth a considerable effort to insure that the spectral and cosine response of all quantum and photometric sensors are as nearly ideal as optically possible. This assures LI-COR customers of the best possible accuracy.

Conversion of Units

Conversion of Photon Units to Radiometric Units

Conversion of quantum sensor output in µmol s^{-1} m^{-2} (400-700 nm) to radiometric units in W m^{-2} (400-700 nm) is complicated. The conversion factor will be different for each light source, and the spectral distribution curve of the radiant output of the source (W_λ; W m^{-2} nm^{-1}) must be known in order to make the conversion. The accurate measurement of W_λ is a difficult task, which should not be attempted without adequate equipment and calibration facilities. The radiometric quantity desired is the integral of W_λ over the 400-700 nm range, or:

$$W_T = \int_{400}^{700} W_\lambda \, d\lambda \qquad 1.$$

At a given wavelength λ, the number of photons per second is:

$$\text{photons } s^{-1} = \frac{W_\lambda}{hc/\lambda} \qquad 2.$$

where h = 6.63 • 10^{-34} J•s (Planck's constant), c = 3.00 • 10^{8} m s^{-1} (velocity of light) and λ is in nm. hc/λ is the energy of one photon. Then, the total number of photons per second in the 400-700 nm range is:

$$\int_{400}^{700} \frac{W_\lambda}{hc/\lambda} d\lambda \qquad 3.$$

This is the integral which is measured by the sensor. If *R* is the reading of the quantum sensor in µmol s^{-1} m^{-2} (1 µmol s^{-1} m^{-2} ≡ 6.022 • 10^{17} photons s^{-1} m^{-2}), then:

$$6.022 \times 10^{17} (R) = \int_{400}^{700} \frac{W_\lambda}{hc/\lambda} d\lambda \qquad 4.$$

Combining Eq. (1) and Eq. (4) gives

$$W_T = 6.022 \times 10^{17} (RHc) \frac{\int_{400}^{700} W_\lambda d\lambda}{\int_{400}^{700} \lambda W_\lambda d\lambda} \qquad 5.$$

To achieve the two integrals, discrete summations are necessary. Also, since W_λ appears in both the numerator and the denominator, the normalized curve N_λ may be substituted for it. Then:

$$W_T = 6.022 \times 10^{17} (RHc) \frac{\sum_i N_{\lambda_i} \Delta\lambda}{\sum_i \lambda_i N_{\lambda_i} \Delta\lambda} \qquad 6.$$

where $\Delta\lambda$ is any desired wavelength interval, λ_i is the center wavelength of the interval and $N_{\lambda i}$ is the normalized radiant output of the source at the center wavelength. In final form this becomes:

$$W_T \approx 119.8\ (R)\frac{\sum_i N_{\lambda_i}}{\sum_i \lambda_i N_{\lambda_i}}\ W\ m^{-2} \qquad 7.$$

where R is the reading in μmol s^{-1} m^{-2}.

The following procedure should be used in conjunction with Eq. (7).

1 . Divide the 400-700 nm range into 'i' intervals of equal wavelength spacing $\Delta\lambda$.

2. Determine the center wavelength (λ_i) of each interval.

3. Determine the normalized radiant output of the source (N_{λ_i}) at each of the center wavelengths.

4. Sum the normalized radiant outputs as determined in Step 3 to find $\sum_i N_{\lambda_i}$

5. Multiply the center wavelength by the normalized radiant output at that wavelength for each interval.

6. Sum the products determined in Step 5 to find $\sum_i \lambda_i N_{\lambda_i}$

7. Use Eq. (7) to find W_T in W m^{-2}, where R is the quantum sensor output in μmol s^{-1} m^{-2}.

The following approximation assumes a flat spectral distribution curve of the source over the 400-700 nm range (equal spectral irradiance over the 400-700 nm range) and is shown as an example.

Given: i = 1
$\Delta\lambda$ = 300 nm
λ_i = 550 nm

$$W_T \approx 119.8\ (R)\left(\frac{N(550)}{550 \times N(550)}\right) = \frac{119.8\ (R)}{550} = 0.22\ (R)\ W\ m^{-2}$$

or

1W m^{-2} ≈ 4.6 μmol $s^{-1}m^{-2}$

This conversion factor is within ±8.5% of the factors determined by McCree as listed in Table 1 (8).

Conversion of Photon Units to Photometric Units

To convert photon units (μmol s^{-1} m^{-2}, 400-700 nm) to photometric units (lux, 400-700 nm), use the above procedure, except

a) Replace Eq. (1) with

$$Lux = 683\int_{400}^{700} y_\lambda W_\lambda d_\lambda$$

where y_λ is the luminosity coefficient of the standard CIE curve with y_λ = 1 at 550 nm and W_λ is the spectral irradiance (W m^{-2} nm^{-1}).

b) Replace Eq. (5) with

$$Lux = 683\ (6.022 \times 10^{17})\ (RHc)\frac{\int_{400}^{700} y_\lambda W_\lambda d_\lambda}{\int_{400}^{700} \lambda W_\lambda d_\lambda}$$

c) Replace Eq. (6) with

$$Lux = 683\ (6.022 \times 10^{17})\ (RHc)\frac{\sum_i y_{\lambda_i} N_{\lambda_i} \Delta\lambda}{\sum_i \lambda_i N_{\lambda_i} \Delta\lambda}$$

d) Replace Eq. (7) with

$$Lux = 8.17 \times 10^4\ (R)\frac{\sum_i y_{\lambda_i} N_{\lambda_i}}{\sum_i \lambda N_{\lambda_i}}$$

e) Replace Step 4 with:

4a) Multiply the luminosity coefficient (y_λ) of the center wavelength by the normalized radiant output (N_λ) at the wavelength for each interval

4b). Sum the products determined in Step 4a to find

$$\sum_i y_{\lambda_i} N_{\lambda_i}$$

The following approximation assumes a flat spectral distribution curve of the source over the 400-700 nm range (equal spectral irradiance over the 400-700 nm range) and shown as an example.

Given:

i = 1 to 31
$\Delta\lambda$ = 10 nm
λ_1 = 400, λ_2 = 410, λ_3 = 420.... λ_{31} = 700
N_λ = 1 for all wavelengths
y_{λ_1} = 0.0004, y_{λ_2} = 0.0012, y_{λ_3} = 0.004....$y_{\lambda_{31}}$ = 0.0041

$$Lux = 8.17 \times 10^4\ (R)\frac{\sum_i y_{\lambda_i}}{\sum_i \lambda_i} = 8.17 \times 10^4\ (R)\left(\frac{10.682}{17050}\right)$$

Lux = 51.2 R, where R is in μmol s^{-1} m^{-2}

Or,

1000 lux = 1 klux = 19.5 μmol s^{-1} m^{-2}

Table 1. Approximate conversion factors for various light sources.
(8) (PAR waveband 400-700 nm)

	Light Source					
	Daylight	Metal halide	Sodium (HP)	Mercury	White fluor.	Incand.
To convert	Multiply by					
W m^{-2} (PAR) to μmol s^{-1} m^{-2} (PAR)	4.6	4.6	5.0	4.7	4.6	5.0
klux to μmol s^{-1} m^{-2} (PAR)	18	14	14	14	12	20
klux to W m^{-2} (PAR)	4.0	3.1	2.8	3.0	2.7	4.0

Radiation Measurement References

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Your comments on the subjects addressed in this report or any other measurement problems are always welcome and will be treated as valuable inputs.

William W. Biggs, Author

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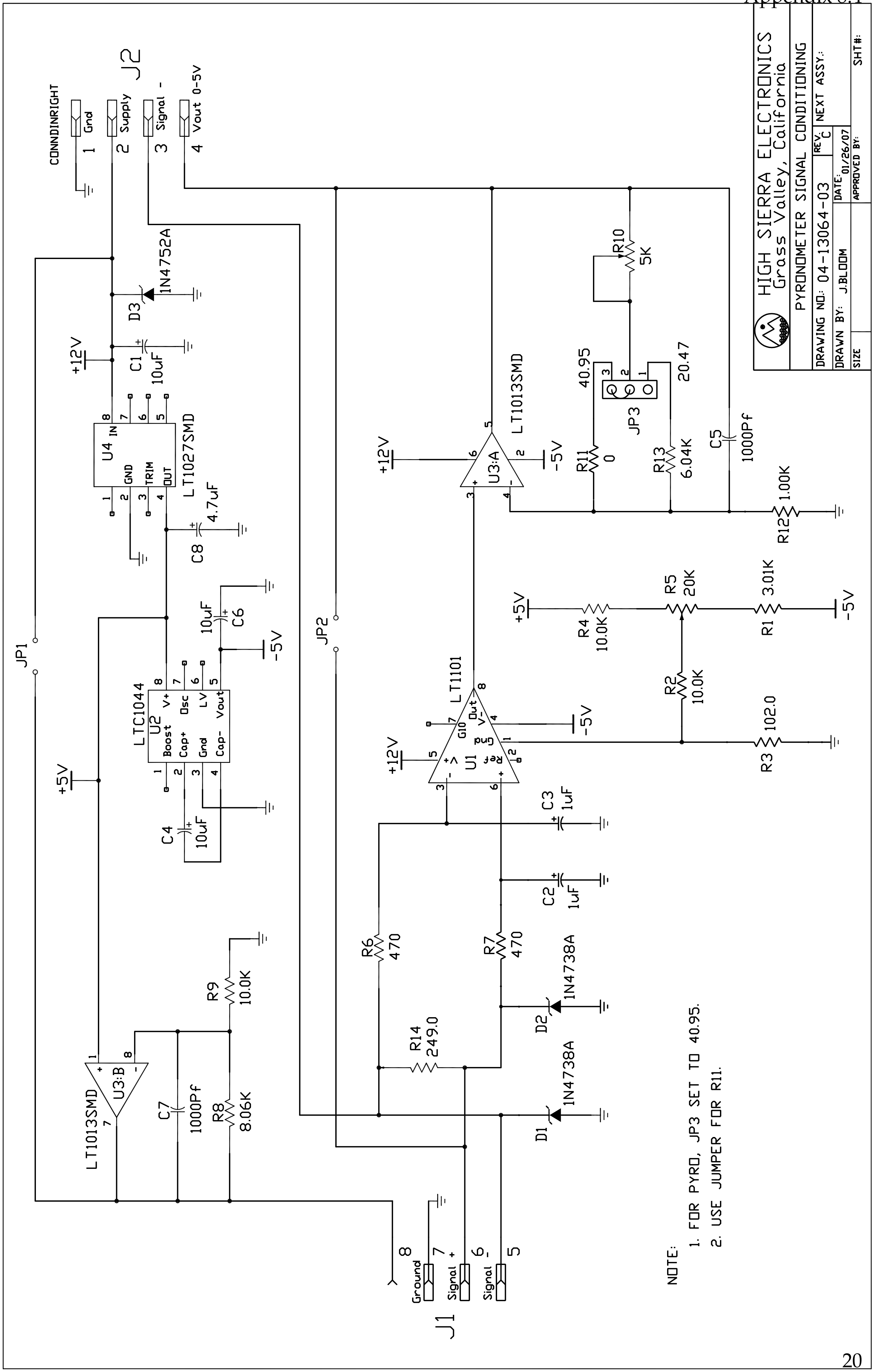
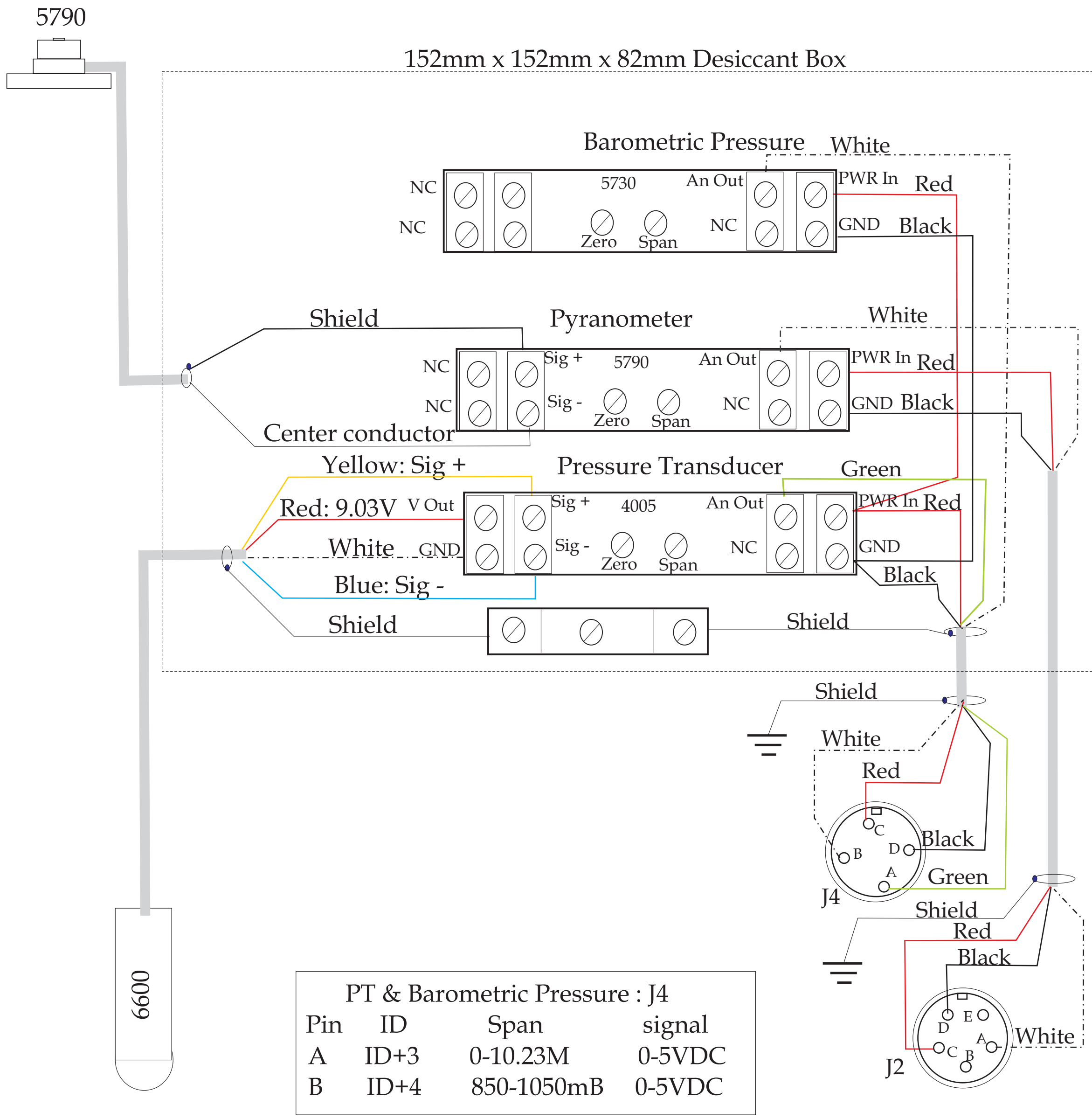

HIGH SIERRA ELECTRONICS
Grass Valley, California
PYRONOMETER SIGNAL CONDITIONING
DRAWING NO: 04-13064-03
REV: C
NEXT ASSY:
DRAWN BY: J.BLOOM
DATE: 01/26/07
APPROVED BY:
SIZE
SHT#:
NOTE:
1. FOR PYRO, JP3 SET TO 40.95.
2. USE JUMPER FOR R11.

Weather Station Sensors: Wire Digram



PT & Barometric Pressure : J4			
Pin	ID	Span	signal
A	ID+3	0-10.23M	0-5VDC
B	ID+4	850-1050mB	0-5VDC

Pyranometer: J2			
Pin	ID	Span	signal
A	ID+6	0-1500 W/M2	0-5VDC

High Sierra Electronics
155 Spring Hill Drive, Grass Valley CA 95945
Phone: (530) 273-2080 Fax: (530) 273-2089

TITLE: Weather Station Sensors Wire Diagram			
MODEL NO.:	DRAWING NO.: 06-13307	REV.: A	APPROVED BY: JS
DATE: 2/21, 2007		DRAWN BY: JAB	
FILE NAME: Argentina 0613306.cdr		SHEET: weather	DO NOT SCALE

High Sierra Electronics

Model 5790 Pyranometer
13064-03 Signal Conditioning Circuit
Calibration Certificate

Customer:	***Argentina***
Sensor type:	***Licor 200SZ***
Serial No:	***PY54879***
Current out (uA) @1000w/sqM:	***97.4***

Date of Calibration:	***2/26/2007***
Range (Watts/sqM):	***1500***
Resistor Value:	***249.3***
Current out (uA) @1500w/sqM:	146.1
base station multiplier:*	0.73278

* : if A/D converter is 11 bit 2047 count
Engineering units: Watts/ sq Meter

Expected output (W/sqM	Input to 13064-03 (mA)	Input to 13064-03 (mV)	Output from 13064-03 (Volts)	Expected Output Volts	Voltage Deviation
300	0.02922	7.285	***0.996***	1.000	-0.004
600	0.05844	14.569	***2.001***	2.000	0.001
900	0.08766	21.854	***2.997***	3.000	-0.003
1200	0.11688	29.138	***4.005***	4.000	0.005
1500	0.1461	36.423	***5.005***	5.000	0.005

Calibrated By: JAB

High Sierra Electronics

Model 5790 Pyranometer
13064-03 Signal Conditioning Circuit
Calibration Certificate

Customer:	***Argentina***
Sensor type:	***Licor 200SZ***
Serial No:	***PY54878***
Current out (uA) @1000w/sqM:	***100.7***

Date of Calibration:	***2/26/2007***
Range (Watts/sqM):	***1500***
Resistor Value:	***249.3***
Current out (uA) @1500w/sqM:	151.05
base station multiplier:*	0.73278

* : if A/D converter is 11 bit 2047 count
Engineering units: Watts/ sq Meter

Expected output (W/sqM	Input to 13064-03 (mA)	Input to 13064-03 (mV)	Output from 13064-03 (Volts)	Expected Output Volts	Voltage Deviation
300	0.03021	7.531	***1.005***	1.000	0.005
600	0.06042	15.063	***2.002***	2.000	0.002
900	0.09063	22.594	***3.004***	3.000	0.004
1200	0.12084	30.125	***4.005***	4.000	0.005
1500	0.15105	37.657	***5.000***	5.000	0.000

Calibrated By: __JAB__

60-5790_cal.xls