Spectrometers for Greenhouse Applications

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November 2023

Overview

Spectroradiometer for continuous spectral data acquisition in a greenhouse for 12 months. Ideally, the spectrometer is self-logging.

- **Budget:** $10,000
- **Spectral Range:** 400-750 nm (minimum)

Note: I use spectrometer and spectroradiometer interchangeably since the spectrometer is the base of the spectroradiometer.

Questions to Address

Kale - Can you send me any papers that you have (if readily available) that discuss:

- spectral irradiance measurements
- diffuse horizontal *spectral* irradiance

What is meant by "continuous" spectral measurements? Are there constraints on frequency of data acquisition?

- 1 spectrum per minute?

Do we need to collect *absolute* or *relative irradiance* values?

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Do we need to perform routine calibration for instrument drift? Weekly? Monthly?

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How do you optimize the integration time, slit width, or other parameters (e.g., neutral density filters)? Electronic control?

- For example, the Gigahertz-Optik BTS2048-VL-TEC-WP spectroradiometer suggests that a new dark signal measurement is acquired for every change in integration time (see the *Technical Specifications*).

Do we need a multi-channel spectrometer/spectroradiometer that can measure the spectrum of a standard source (e.g., a deuterium lamp or other thermal source)?

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Do we need to perform concurrent measurements with a stable, integral photodiode?

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What spectral resolution is required/expected?

- Presumably, 1 nm resolution is sufficient.
- Note that the CIE standard luminosity function is stored with 5 nm resolution.

How should we mount the spectrometer? Receiving optics facing vertically?

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Preference towards cosine diffuser vs. fiber optic cable?

- (AH) It would be easier to use optics directly; mounting a fiber optic cable would require extra pieces.
- What size fiber optic cable core is required? (For example, OceanOptics has fibers with diameters ranging from 50-600 micron)

Do fiber optic cables cover a broad enough spectral range?

- OceanOptics has a couple options, which cover the desired spectral range (400-750 nm).
- Fibers are pretty inexpensive ($150-$200).

Are there any wavelength-dependent corrections that need to be applied for spectral components near the edges?

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What environmental considerations are required?

- Humidity ranges?
- Temperature ranges?

Miscellaneous Topics

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I. Data Storage Considerations

Spectral *irradiance* contains a lot more information than integrated quantity (irradiance). I will assume that spectral irradiance has units of [$W/m^2/nm$] since most spectrometers use a grating (gratings) to disperse light; in practice, the as-measured quantity will probably be a

voltage. Gratings disperse light in equal wavelength bins; assume a resolution of 1 nm.[1] Here's a quick back-of-the-envelope calculation for data storage requirements.

- Data Representation: double-precision floating-point number
  - N_B = 8 B/point
- Spectral Range: 350-1000 nm
  - $N_X = N_Y$ = 651 points/axis
- Resolution:
  - dx = 1 nm
- Spectral Measurements: Assume 1 min. integration time with one spectrum collected every 2 min. (e.g., 1 minute on, 1 minute off)
  - Integration Time, t_{int} = 1 min.
  - Collection Frequency, f_s = 0.5 spectra/min.
- Storage Requirements (B = bytes):
  - $N_S = 2N_X$ = 1302 points/spectrum
  - $\boldsymbol{B_S = N_B N_S =}$ **10416 B/spectrum**
  - $N_D = f_s$ (24 hr.)(60 min.) = 720 spectra/day
  - $\boldsymbol{B_D = N_D B_S}$ **= 7.5 MB/day**
  - N_Y = (365 day/year) N_D = 262,800 spectra/year
  - $\boldsymbol{B_Y = N_Y B_S}$ **= 2.7 GB/year**

A crude estimate for memory requirements is **0.01 MB/spectrum**. Data could be interpolated to a common wavelength axis, effectively reducing data storage requirements by a factor of 2; instead, I assumed that we store the raw, as-collected data. No data compression techniques are employed. In addition, I have not accounted for the storage of any metadata (e.g., epoch time of acquisition, temperature, humidity, linked data like pyranometer measurements, etc.).

Kale - have you used the HDF5 data format before?

- (AH) I've never used it before, but it looks interesting for storing linked data. Using simpler file formats like .csv might be easier.

[1] Resolution depends on a number of factors, like slit width, blaze angle of the grating, etc.

II. Available Datasets and Global Monitoring Laboratories

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National Solar Radiation Database (NSRDB):

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Typical Meteorological Year (TMY3):

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National Renewable Energy Laboratory (NREL):

System Advisor Model (SAM) -

ESRL Global Monitoring Laboratory:

(Website)

Other:

- Woods *et al.*, 2022 (https://doi.org/10.1007/s11207-022-02001-9); Long-Term Trend Analysis in the Solar Radiation and Climate Experiment (SORCE)/Spectral Irradiance Monitor (SIM)

Spectrometers and Spectroradiometers

Requested quotes from:

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Common to Most Spectrometers:

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Quick Summary:

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Pros:

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Cons:

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Relevant Models:

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(Model):

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I. Gigahertz-Optik

Overview

This is my first choice in terms of design and capabilities (very close with the StellarNet SolarRad).

Pros

- Pretty impressed with the BiTec sensor technology (mutual correction from photodiode correction; slow drift allows compensation for spectrum); this seems like a huge benefit/draw
- Previously used for annual (1 year) acquisition of outdoor, UV index data
- Use of BiTec Sensor allows for “self-calibration” of spectral data (slow drift, robust photodiode used as correction and has same field-of-view as array detector)
- Parallel processing

Cons

- Software is Windows-based (.dll files) - Optional software development kit S-SDK-BTS2048 for user software set-ups based on .dll‘s in C, C++,C# or in LabView.

Relevant Models

BTS2048-VL-TEC

- Cooled temperature controlled BiTec sensor for accurate measurements
- Very short measuring times (electronic shutter)

BTS2048-UV-S

Software:

- https://www.gigahertz-optik.com/en-us/product/s-bts2048/

BiTec Sensor Information (link)

Consists of two detectors/sensors:

1. Integral photodiode
2. Spectral-array spectrometer

Independent detectors (can be used separately)

Traceable Calibration of Spectroradiometers for Measuring Solar Radiation

- https://www.gigahertz-optik.com/en-us/app-groups/solar-radiation/
- https://www.gigahertz-optik.com/en-us/product/BN-9101/

References

1. Knowledge Base of Gigahertz-Optik (Homepage)
    a. Spectral Mismatch Correction Factor (link)
    b. Measurements of PAR (link)
2. Measurement of Solar Irradiance to Calculate the UV Index
3. https://www.gigahertz-optik.com/en-us/product/bts2048-vl-tec/
4. https://www.gigahertz-optik.com/en-us/products/cat/spectroradiometers%20for%20radiometry/
5. https://www.gigahertz-optik.com/en-us/product/bts2048-vl-tec-wp/

II. StellarNet Inc.

Overview

This is my first choice if software is the primary concern. The SolarRad spectroradiometer is reasonably priced ($5325), and comes with all of the required extensions. StellarNet provides the most universal software support, as well as a lot of options for configuring your own software. They provide support for digital communication via Wi-Fi and/or mobile apps, as well as support for Linux and Raspberry Pi. There is an add-on SMART Control spectrometer controller that allows you to run one of their applications (e.g., “Radiometry”). The documentation and manuals provided online are terse, but might be sufficient for setting up your own programs (a lot of stuff is written in Python, so it should be easy to read).

Pros

- TBD

Cons

- TBD

Miscellaneous

- Integration Times: 1 ms to 65 s (here)
- Ruggedized: The detachable spectrograph assembly and control electronics are protected inside a rugged metal enclosure, suitable for portable, process, lab, and field applications.

Relevant Models

1. Solar-RAD (200-1080 nm)
2. BLACK-Comet-SR (200-1080 nm)

SolarRad (300-1100 nm)

Price: $5325

Range: 300-1100 nm

Includes:

- **BLACK-Comet-CXR-SR concave grating spectrometer** (link)
- **F600-UV-VIS-SR Fiber Optic Cable** (link) - Armored, 2 meters, solarization resistant fiber optic cable
- **CR2 Cosine Receptor** (link) - ¼" diameter UV-VIS-NIR cosine receptor which uses a polymer diffuser for 200-1700 nm and 180° FOV
- **CR2-TP Positioning Tripod** (link) - miniature tripod for mounting the CR2, CR1-UVN, or integrating spheres.
- **IRRAD-CAL-UVN NIST Traceable Standard** (link)
- **IRRAD-CAL Certificate of Calibration** (link)

Upgrades:

- **BLACK-Comet TEC Upgrade** ($1750) - Thermo Electric Cooler (TEC) upgrade for low light LED testing to improve measurement sensitivity and detection capability.
- **SMART Control Interface Upgrade** ($2000)

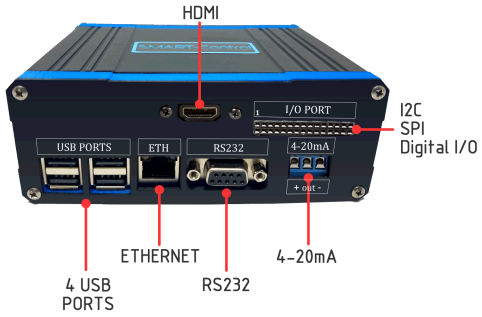
SMART Control Interface Upgrade

From the online documentation:

> "*The SMART-Control device offers communication flexibility and application specific customization for any StellarNet spectrometer. This add-on interface includes an integrated **CPU** with **1GB RAM** and many communication protocols such as **RS232**, **SPI**, 4-20mA **Analog** for PLCs, **Digital I/O**, **Ethernet**, **Wifi** and many other options. The SMART-Control allows customers to move their spectrometers into process or OEM environments and stream their selected real world data.*"

Some Nice Features:

- UPS Back-up Battery (3 hrs.)



Software

There are a lot of software options to choose from, as well as direct support for Linux and Raspberry Pi.

A. StellarPro Software

Included **free** with every **spectrometer** for Windows, Mac, and **Linux**; software also includes an app for radiometry, see here)

> *"Our new StellarPro Software is a combination of our popular SpectraWiz software with advanced tools and an application module style interface, be prepared to have your mind blown. Built-in modules for Radiometry, Colorimetry, Chemical Absorption/Kinetics, Chemometrics, Spectral ID, Raman, Multichannel, Haze, & Thin-Film.*
>
> *Our new StellarPro software also has integrated spectral preprocessing such as baseline subtraction, spike removal, and derivative view. Spectral matching, PLS Calibration model development, Classification algorithm, and run-time deployment are all included in this new software suite. StellarPro has user permission settings, login, and reporting to export all of your data in one place. Additional apps for Haze, Thin Film Analysis, and more are also included!"*

B. StellarRad for iPhone and Android

Light Spectral Analysis App (link)

> *"The StellarRAD App for all WiFi-enabled StellarNet spectrometers makes real-time light measurement quick and easy. Acquire full spectrum analysis of LEDs, lamps, lasers, solar or*

grow lights, and just about any type of luminaire from ultraviolet through the visible and near-infrared!

*This intuitive app lets users **control their spectrometer** and capture basic and more advanced light measurement parameters such as **spectral irradiance** and lumens. Colorimetric analysis such as CRI (color rendering index), CCT (correlated color temperature), xy chromaticity, and much more are included. Easily save and export your data and full spectral graph as an .IRR text data file, screenshot, and/or PDF report with all parameters listed."*

C. SpectraWiz Mobile for Linux/RasPi (link)

"Our SpectraWiz Mobile application software is designed to run directly on SMART-Control spectrometer interfaces (Linux/RasPi) and connect directly to mobile devices. Using the local access point or WiFi you can easily log in and run applications for General Spectroscopy, Radiometry, Colorimetry, and Concentration Analysis.

*The SpectraWiz Mobile application scripts are **written in Python** and provided free with the purchase of a **SMART-Control**. These **source codes**, which can be further customized to suit each user's requirements, can also be **purchased** separately. OEM customers can add their logos or additional computations and industrial customers can set their spectrometer and stream their data to PLCs or other process monitoring platforms."*

D. Spectrometer Python Application Driver (Windows, Linux, RasPi, Mac)

Python Driver and Demo Scripts (link)

*"StellarNet also offers our new Python USB spectrometer driver and basic Application Development Kit (ADK) with each spectrometer. Our StellarNet Python Driver, **stellarnet_driver,** and **stellarnet.hex files** can be downloaded upon request once our Software License Agreement is filled out and returned (please provide details of your operating system and all requirements).*

*In addition, we also provide a simple data acquisition script written in python 2 & 3 (**stellarnetdemo.py**) that can communicate with **stellarnet_driver** and perform a simple operation to set device parameters and acquire spectrum. Methods and functions for driver callback are explained below."*

E. Spectrometer Web Server (Flask RESTful API)

Python Driver and JSON Interface (link)

> *"Our StellarNet Python Driver and JSON interface is now available for web server implementation which **allows fast control and access to JSON formatted data** by applications on the same machine or across the LAN or Internet. A RESTful API allows multiple users to access multiple spectrometers in parallel using simple HTML formats.*
>
> *This driver and web server have been **tested on many Linux distributions** and the project should be transportable to other platforms as well. Among the features of these implementations are a numeric configuration ID that increments whenever the parameters of a spectrometer are changed (essential for multi-user or multi-process applications) and a timestamp in milliseconds for each spectrum returned (helpful for process control techniques such as PID). The driver and web server operate in non-privileged user-space without administrative permissions."*

References

1. https://www.stellarnet.us/systems/spectroradiometers-general-lighting/

III. OceanOptics®

Overview

Secondary to StellarNet and Gigahertz-Optik options.

Pros

- Lots of add-ons (cosine diffusers, calibrated sources)
- Configurable software with SDK (OceanDirect)
- FX spectrometer has 8 programmable GPIO pins (10 us to 10 s integration times; 200-850 nm; 1.33 nm FWHM)
- All support Wi-Fi protocols

Cons

- Expensive compared to the StellarNet spectrometers; the OceanOptics devices are better served in fields where high-resolution spectroscopy is important.

Relevant Models

1. **HR2 VIS-NIR Spectrometer (200-1100 nm)** - High-Resolution Spectrometer (N/A)
2. **HDX Spectrometer (200-1100 nm)** - Miniature Spectrometer (~$6300)
3. **FX VIS-NIR Spectrometer (350-1000 nm)** – High-Speed Spectrometer (~$5000)
4. **ST VIS Microspectrometer (350-810 nm)** - Miniature Spectrometer ($1600)

Note: All quoted prices are from what I could find on Google (prices are not listed on their website; I am waiting for quotes on all four devices).

HR2 VIS-NIR Spectrometer (200-1100 nm)

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HDX Spectrometer

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FX VIS-NIR Spectrometer

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ST VIS Microspectrometer (350-810 nm)

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Miscellaneous Details

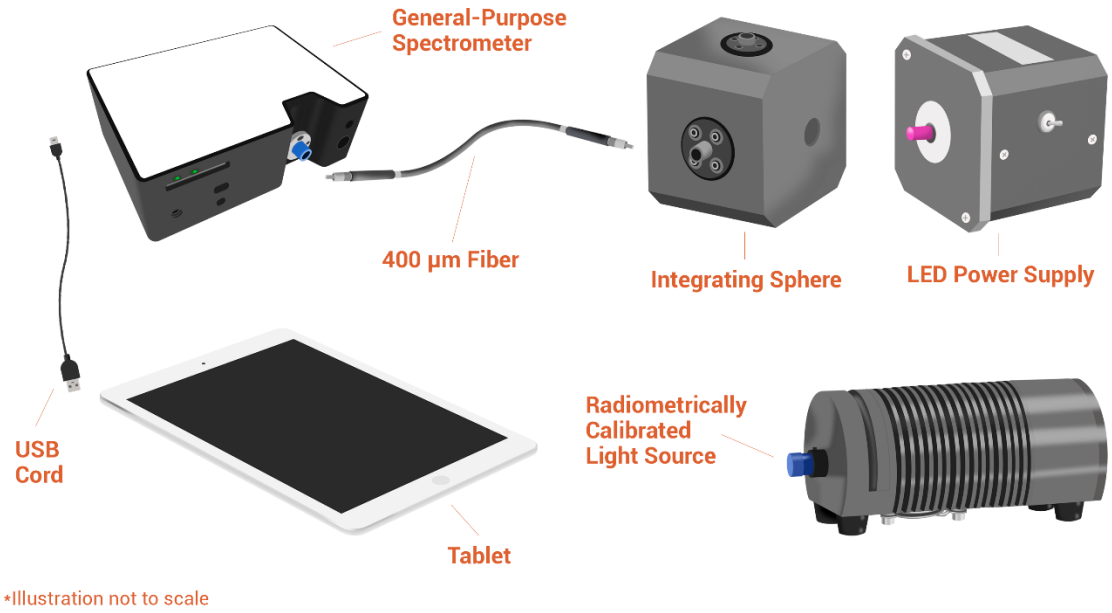
- Operation Temperature: 0 C to 55 C
- Storage Temperature: -30 C to 70 C

Additional Information

[Cosine-Correctors]

[Radiometric Calibrated LIght Sources]

[Solarization Resistant Optical Fibers] - Starting at $165 (pretty standard)



(See [this page] for more details)

References

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IV. Apogee Instruments

Overview:

Spectroradiometer packages are essentially StellarNet spectrometers with a few additional items (fiber optic cable, shoulder bag, Apogee cosine-corrected radiometric head with black cap). I couldn't find much information on the Apogee detector. The radiometers also use the StellarNet Windows software.

Just buy directly from StellarNet. The StellarNet **Solar-Rad** comes with more useful accessories, gives you direct access to the StellarNet software (free with purchase), and is priced at **$5325** compared to the comparable Apogee instrument, PS-200, at **$5595**. The price difference compared to the StellarNet spectrometer is substantial - for the base spectrometer, the StellarNet BLACK-Comet-SR is $3950, which is roughly $1600 less than the Apogee instrument). The Apogee accessories are pretty inexpensive - for example, the fiber optic cable is <$200.

Pros:

It is a StellarNet spectrometer.

Cons:

See the overview.

Relevant Models:

- PS-100 (350-1000 nm, 1 nm resolution); $4995.00
- PS-200 (350-850 nm, 0.85 nm resolution); $5595.00
- PS-300 (300-1000 nm, 1.5 nm resolution); $6625.00

References

1. StellarNet Software Download (PS-100, PS-200, PS-300)
1. https://www.apogeeinstruments.com/spectroradiometers/
2. https://www.apogeeinstruments.com/lab-spectroradiometer-support/
3. https://www.apogeeinstruments.com/microcache-bluetooth-micro-logger/