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Measuring the Solar Radiation Spectrum in 4 planes for Daylight and PV Applications

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Abstract

For solar energy, radiative environment simulations and forecasts are becoming major challenges. To be validated, models have to be compared with ground measurements. The latter should be quite exhaustive: diffuse and direct components, in various representative planes, spectrum, sky images… They need to be reliable, providing uncertainties and going through a systematic quality control. This presentation describes our measurement system, the calibration of its components (optical fibers and spectrometers), and the error characterization. These measurements will be used to validate atmospheric information from satellites as well as spectral irradiances computed by various RTMs. Our objective is to produce long term variations of the solar spectrum in Lyon and recommend a modeling procedure.

1. Context

1.1. Solar spectrum fluctuating and different sensor responses

Solar energy is abundant and capable of providing much of our energy needs. It has several uses: photovoltaic, biomass (wood energy, biogas, biofuel), daylighting... For each use, its potential depends on the match between the spectral response of the collector (silicon, retina photoreceptors...) and the local solar spectrum. Increasing the performance of solar technologies by making the most of its spectrum (sun plus sky), requires a better understanding of its long term variations.

1.2. Radiative Transfer Models requirements

Radiative Transfer Models (RTMs) could be used to produce routinely the spectral irradiance received in the plane of a solar collector and build this climatology, anywhere on earth. The accuracy of RTMs depends on how well daily atmospheric constituents are known at the site. This information is becoming available from satellite data. Spectral measurements are needed to validate the use of RTMs with satellite derived atmospheric information.

1.3. The measuring station

Since 1992, our laboratory has been maintaining in France, a measuring station specialized in daylight (Fig 1). This station, part of the CIE-IDMP international network (CIE, 1994), measures the diffuse and global horizontal sky illuminance, the global illuminances in four vertical planes as well as the diffuse horizontal, global horizontal and direct normal irradiances. In 2012, we decided to add continuous spectral measurements to the station. We chose to measure the spectral irradiance in 4 planes useful for daylight and photovoltaic applications: 1 direct (perpendicular to the sun), 3 global (horizontal, vertical east, south inclined at 45°). We decided to use 4 spectrometers (Ocean Optics USB 650/4000) coupled to optical fibers fitted with diffusers.

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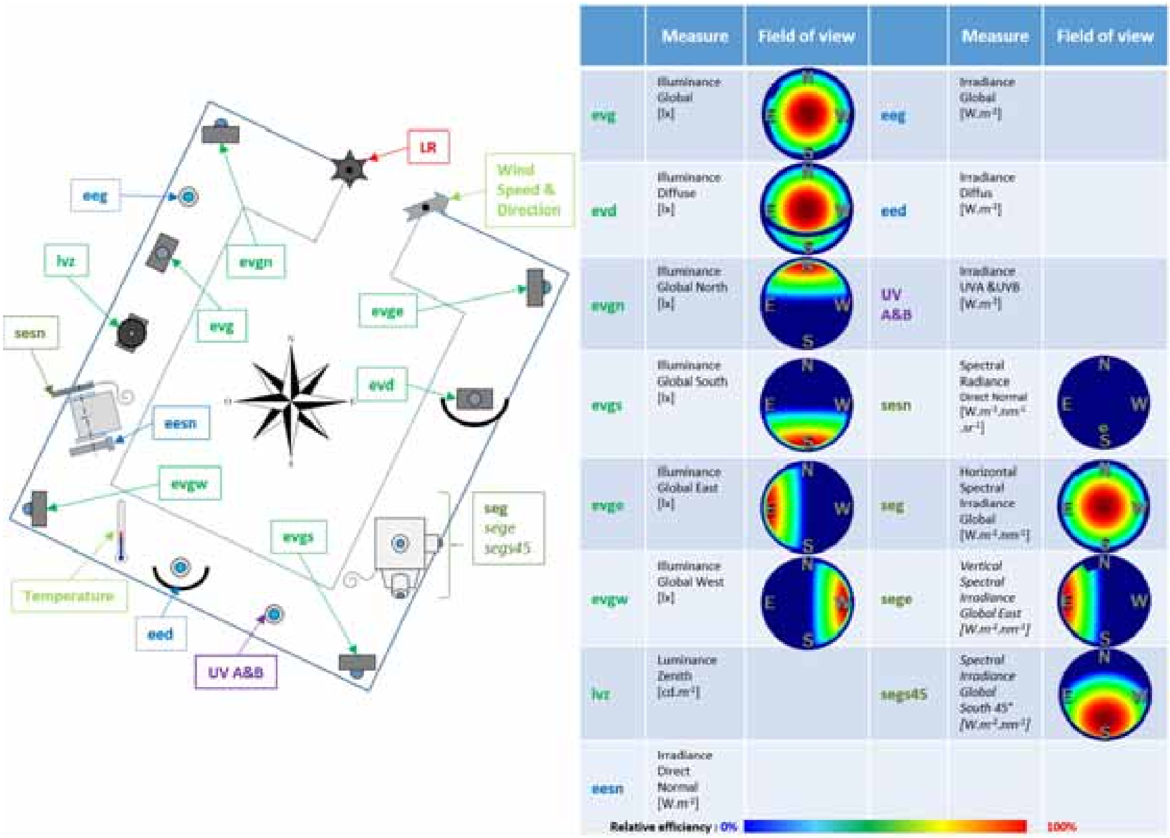


	Measure	Field of view		Measure	Field of view
evg	Illuminance Global [lx]		eeg	Irradiance Global $[W.m^{-2}]$	
evd	Illuminance Diffuse [lx]		eed	Irradiance Diffus $[W.m^{-2}]$	
evgn	Illuminance Global North [lx]		UV A&B	Irradiance UVA &UVB $[W.m^{-2}]$	
evgs	Illuminance Global South [lx]		sesn	Spectral Radiance Direct Normal $[W.m^{-2}.nm^{-1}.sr^{-1}]$	
evge	Illuminance Global East [lx]		seg	Horizontal Spectral Irradiance Global $[W.m^{-2}.nm^{-1}]$	
evgw	Illuminance Global West [lx]		sege	Vertical Spectral Irradiance Global East $[W.m^{-2}.nm^{-1}]$	
lvz	Luminance Zenith $[cd.m^{-2}]$		segs45	Spectral Irradiance Global South 45° $[W.m^{-2}.nm^{-1}]$	
eesn	Irradiance Direct Normal $[W.m^{-2}]$				

Fig 1: ENTPE CIE-IDMP Station with its instruments. For some of them you can see the simulated field of view: this information is useful for inter-comparison between several instruments (see 4. Outlook).

2. The spectral Measurement system

2.1. Hardware

Our spectral acquisition is composed of four measuring lines:

three for spectral irradiance measurements with different orientations:

- seg: global horizontal, which looks at the zenith,
- segs45: south global 45°, looks at the south with an altitude angle of 45° (local latitude),
- sege: east global vertical, looks at the east with an altitude angle of 0°,

the fourth one for the spectral radiance of the sun:

- sesn: spectral radiance of the sun.

Each line consists of: a cosine diffusor for photon collection and a 15 m optical fiber guiding the radiation to a spectroradiometer. These spectrometers are located in a small office room below the station. All these parts were bought from the Ocean Optics Company. For the purpose of measurement stability and quality, the spectrometers are installed in a thermostatic cabinet.

The three irradiance lines are preserved from weather conditions with their own glass dome. They end with three spectroradiometers USB650 with a 5nm spectral resolution and a raw spectral bandwidth from 350 to 1000nm.

For the fourth line, the diffusor is fitted in a tube to limit its field of view to the sun. This tube is fixed on a STR-22 sun tracker from the Eko Instrument Company. Here, the spectrometer is a USB4000, with a 1nm spectral resolution and a raw spectral bandwidth from 345 to 1040nm.

2.2. Acquisition procedure and software

We had the choice between different kinds of acquisitions:

- A single acquisition per minute using an integration time optimized for the observed radiation,
- A few acquisitions per minute using different integration times (High Dynamic Range acquisition or HDR),
- A continuous acquisition using a short integration time

For reasons that we explain below, we have chosen the last acquisition method: a continuous measurement using a 200ms integration time (about 292 spectrums every minute due to the latency). Spectrums are first recorded, in a synchronous way for the four lines, by the OceanOptics‘s software: SpectraSuite. Then, they are processed by our java code, apart from the first software, according to two methods.

The first one gives us a one minute spectral acquisition. It consists in the integration of one minute of measurements for one spectrum. It provides its mean values, the range of variability and the uncertainties associated to these mean values (see §2.3).

The second one gives us an integrated weighted spectrum for each second. It creates one second collections of spectrums, uses a filter function (for instance, the photopic function) to weight these values, and then proceeds to a spectral integration. In this way, we produce each second a data and its uncertainty related to the filter used.

Advantages

The dissociation between the OceanOptics acquisition software and the java pre-processing code allows maintaining our code without stopping the acquisition.

Keeping a constant integration time avoid a long and difficult study of measurement noise and signal sensibility for each integration time. Here, we focus on a well-chosen exposure time, constant during all the year.

The entire working time of the spectrometer is dedicated for an exploitable acquisition. Each acquisition is useful on its entire spectral range. It means that each detectable photon is effectively recorded, and never saturates the signal. The integration time is selected to have an unsaturated signal all over the year. There is no loss of information unlike the two methods previously excluded.

Finally, the large number of measurements in a minute has a significant benefit: it allows some statistical analysis of radiation variation and measurement uncertainty.

Drawback

A large proportion of measurements are underexposed, so the dark signal is relatively too high. We need to add an efficient way to process the signal to correct this drawback.

2.3. One minute spectral acquisition

Every ten minutes, the raw spectrums $X(\lambda)$, recorded by the acquisition software, are stored in a one minute collection. It gives about $N = 292$ spectrums with a $\tau_0 = 200ms$ of integration time for each collection. These collections are identified as “Dark” or “Signal” (see below). For each collection, we build a file with a specific header (Fig 2).

```
|______________INTEGRATED SPECTRUM______________
MEASUREMENT                   :   SEG
STARTING DATE                 :   Monday 04/08/2014 19h14min00sec, GMT+02:00
ENDING DATE                   :   Monday 04/08/2014 19h14min59sec, GMT+02:00
USER                          :   guillaume.tourasse
SPECTRO                       :   USB2G36553
SINGLE INTEGRATION TIME [s] :     0.2
TOTAL INTEGRATION TIME [s]  :     58.60015
NUMBER OF SPECTRUM            :   293
SINGLE SPECTRA AVERAGED       :   1
BOXCAR                        :   0
PIXELS NUMBER                 :   651
PART OF THE DAY               :   1154
KIND OF MEASURE (OUT=0,DARK=1,SIGNAL=2,CALIBRATION=3) : 2
DARK FILE USED                :   C:\SPECTRAL\VAULX\DARK_SIG\DARK - SEG - 15-07-2014.txt
TRANSFER FUNCTION FILE USED :     C:\SPECTRAL\VAULX\TRANSFER_FCT\TRANSFER_FUNCTION - SEG - 15-07-2014.txt
```

Fig 2: Header for a “one minute spectral acquisition” file. It contains all information about the related acquisition.

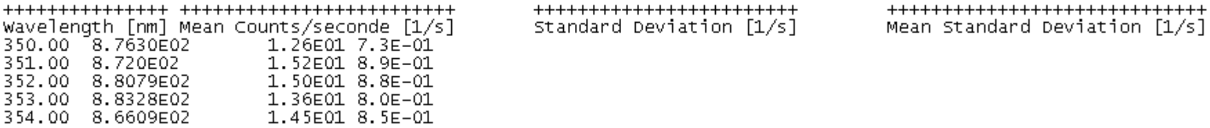
After the header, there are four columns which represent the spectrum and its standard deviations (Fig 3). The first column is always the wavelengths in nanometer.

“Dark” File

This identification is for the files recorded during the hour of the “middle of the night”. That is the hour at the same temporal distances from the sunset and the sunrise. In these files, the dark mean spectrum $\bar{D}(\lambda)$, its standard deviation $\sigma_D(\lambda)$ and its mean standard deviation $\sigma_{\langle D\rangle}(\lambda)$ are computed $(eq. 1,2,3)$. The unit is count/second. They are defined as follows:

$$\bar{D}(\lambda) = \frac{\bar{X}(\lambda)}{\tau_0} \quad ; \quad \sigma_D(\lambda) = \frac{\sqrt{\overline{X^2}(\lambda) - \bar{X}^2(\lambda)}}{\tau_0} \quad ; \quad \sigma_{\bar{D}}(\lambda) = \frac{\sigma_D(\lambda)}{\sqrt{N}} \qquad (eq. 1,2,3)$$

The file structure is shown in the figure below (Fig 3).



```
+++++++++++++++ +++++++++++++++++++++++++         +++++++++++++++++++++++++         +++++++++++++++++++++++++++++
wavelength [nm] Mean Counts/seconde [1/s]         Standard Deviation [1/s]          Mean Standard Deviation [1/s]
350.00  8.7630E02        1.26E01 7.3E-01
351.00  8.720E02         1.52E01 8.9E-01
352.00  8.8079E02        1.50E01 8.8E-01
353.00  8.8328E02        1.36E01 8.0E-01
354.00  8.6609E02        1.45E01 8.5E-01
```

Fig 3: Spectrum file structure. In order to decrease the file size and to obtain a consistent format, the number of significant decimals are based on the mean standard deviation value $\sigma_{\langle D\rangle}(\lambda)$.

“Signal” File

The spectrums identified by “signal” are recorded during the day, between sunrise and sunset. If the dark signal $D(\lambda)$ and the transfer function $T(\lambda)$ have been defined for this measurement line, we use them to convert the raw spectrums $X(\lambda)$ to the corresponding signal (spectral irradiance or spectral radiance). We will write it generically $S(\lambda)$ in the following. For this kind of measurements, three spectrums are recorded each minute: the signal mean value $\bar{S}(\lambda)$, its total standard deviation $\sigma_S(\lambda)$, and the standard deviation $\sigma_{SS}(\lambda)$ which is the uncertainty if the radiation source was stable and equal to its mean value $\bar{S}(\lambda)$ (SS: Stable Source) (eq. 4,5,6). We’ll see the distinction between these two standard deviations in §2.5.

$$\bar{S}(\lambda) = \frac{\frac{\bar{X}(\lambda)}{\tau_0} - \bar{D}(\lambda)}{\bar{T}(\lambda)} \qquad (\text{eq. } 4)$$

$$\sigma_S(\lambda) = \left| \frac{\frac{\bar{X}(\lambda)}{\tau_0} - \bar{D}(\lambda)}{\bar{T}(\lambda)} \right| \sqrt{\frac{\left(\frac{\sigma_X(\lambda)}{\tau_0}\right)^2 + \sigma_{\bar{D}}{}^2(\lambda)}{\left(\frac{\bar{X}(\lambda)}{\tau_0} - \bar{D}(\lambda)\right)^2} + \left(\frac{\sigma_{\bar{T}}(\lambda)}{\bar{T}(\lambda)}\right)^2} \qquad (\text{eq. } 5)$$

$$\sigma_{SS}(\lambda) = f\left(\bar{S}(\lambda)\right) \qquad (\text{eq. } 6)$$

with:

$$\sigma_X(\lambda) = \sqrt{\overline{X^2}(\lambda) - \bar{X}^2(\lambda)} \qquad (\text{eq. } 7)$$

The measurements $D(\lambda)$, $T(\lambda)$ and $X(\lambda)$ are independent. This absence of correlation allows the definition of $\sigma_S(\lambda)$,
$f\left(\bar{S}(\lambda)\right)$ is given by the study of $\bar{S}(\lambda)$ and $\sigma_S(\lambda)$ for a stable radiation (see §2.5).

2.4. One second integrated acquisition

This kind of acquisition offers a finer temporal resolution for some spectral range of interest (weighted or not with some spectral efficiency). For this purpose, the spectrum $\bar{S}(\lambda)$ is multiplied by a filter $F(\lambda)$ of your choice. Then, the obtained spectrum is integrated on the K wavelengths.

Here are some of these filters:

- The CIE's photopic curve,
- Spectral sensitivity of our fisheye camera,
- A few spectral bands for O_2 and water.
- Some molecular free spectral bands,

It is also possible to add an uncertainty $\sigma_F(\lambda)$ to these filters. This way, we obtain for each second and filter, an integrated value ξ with its uncertainty σ_ξ $(\text{eq. } 8{,}9)$ corresponding to the one second signal $\bar{S}(\lambda)$ $(\text{eq. } 4)$.

$$\xi = \Delta\lambda \sum_{k=1}^{K} F(\lambda_k)\bar{S}(\lambda_k) \qquad (\text{eq. } 8)$$

$$\sigma_\xi = \Delta\lambda \sqrt{\sum_{k=1}^{K} \left[\left(\bar{S}(\lambda_k)\sigma_F(\lambda_k)\right)^2 + \left(F(\lambda_k)\sigma_{SS}(\lambda_k)\right)^2\right]} \qquad (\text{eq. } 9)$$

During this second, the radiation source is considered as a stable one. So the most significant value to represent the uncertainty is $\sigma_{SS}(\lambda)$. If the source is stable, we have no correlation between the wavelengths, so we can define σ_ξ as above.

2.5. Calibration

It is essential to define the spectral sensitivity of each line. This calibration is performed in two steps. The first step is a relative spectral calibration using a reference spectroradiometer. The second step is an absolute calibration consisting in an integration with the photopic filter and a comparison to illuminances measured by a reference cell.

Relative spectral calibration

For this part, we use as a reference, the recently calibrated spectrometer, SPECBOS 1211UV from the JETI Techniche Instrumente GmbH. After the comparisons of OceanOptics's spectrums and SPECBOS's spectrums we obtain the spectral transfer functions for each complete line (diffusor+15m optical fiber+spectrometer) and their related uncertainties.

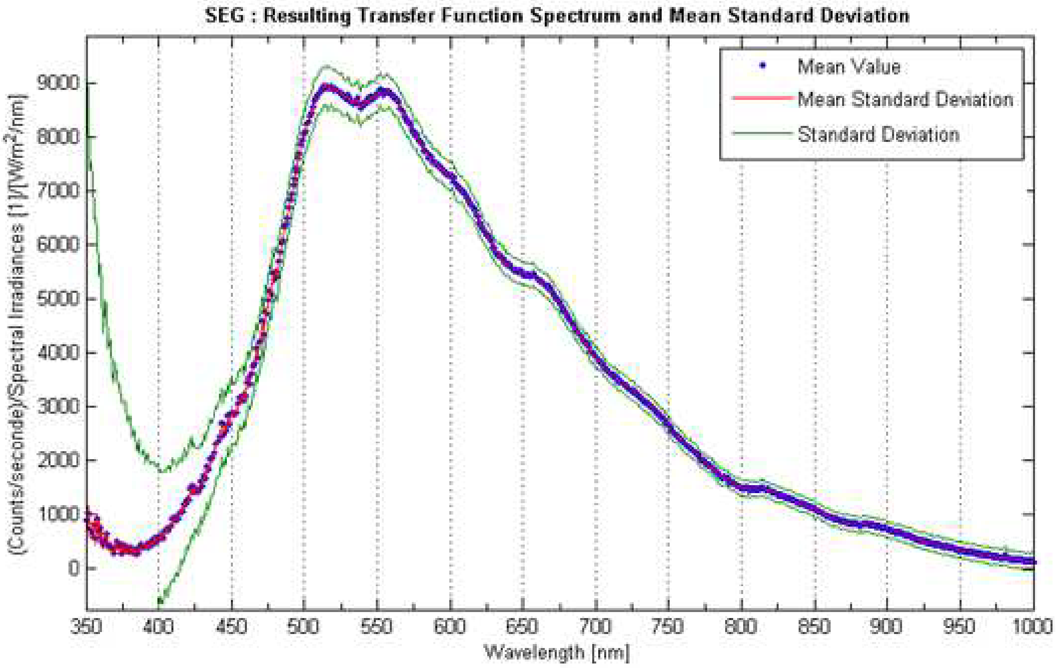


Fig 4: Spectral transfer function for the seg line. The strong uncertainty in the UV band is easily explained by the halogen radiative source used for the calibration. Its temperature is not high enough to obtain a significant radiation in this part. Another important observation: even if the spectrometer's spectral range is quite important (350-1000nm), the effective spectral range due to the entire acquisition line is far narrower (the measurement is not exploitable below about 400nm and above about 800nm).

Absolute calibration

This second step of calibration has been made after a first series of “one second integrated” acquisitions of illuminances computed from the Ocean Optics lines (enough to carry out a statistical study). These illuminances were compared with those from a BAP 30 FCT cell from LichtMessTechnik (LMT) GMBH Company. This cell is used on our CIE-IDMP station for global illuminance measurements. After comparison, we obtained the final correction factor for each Ocean Optics line.

Uncertainties estimation related to known mean values

We need to know in what proportions signal variability is due on one hand to measurement noise and; on the other hand, to sky radiation variability. This is the comparison (seen above) between $\sigma_S(\lambda)$ which takes into account the whole variability and $\sigma_{SS}(\lambda)$ which represents the line’s noise measurement for a stable source. If $\sigma_S(\lambda) >> \sigma_{SS}(\lambda)$: the sky radiation fluctuated during the measurement and if $\sigma_S(\lambda) \approx \sigma_{SS}(\lambda)$: the sky radiation was stable (or the spectrometer was blind for this spectral range). To evaluate measurement noise, we analyze measurements of a stable sky (no clouds). We use a series of one minute measurements so that, the radiation doesn’t fluctuate enough, during each acquisition, to be a problem. In this configuration, the standard deviation recorded is only due to the noise of measurement. After signal processing, we can see the link between mean value $\bar{S}(\lambda)$ and standard deviation $\sigma_{SS}(\lambda)$ (see Fig 5).

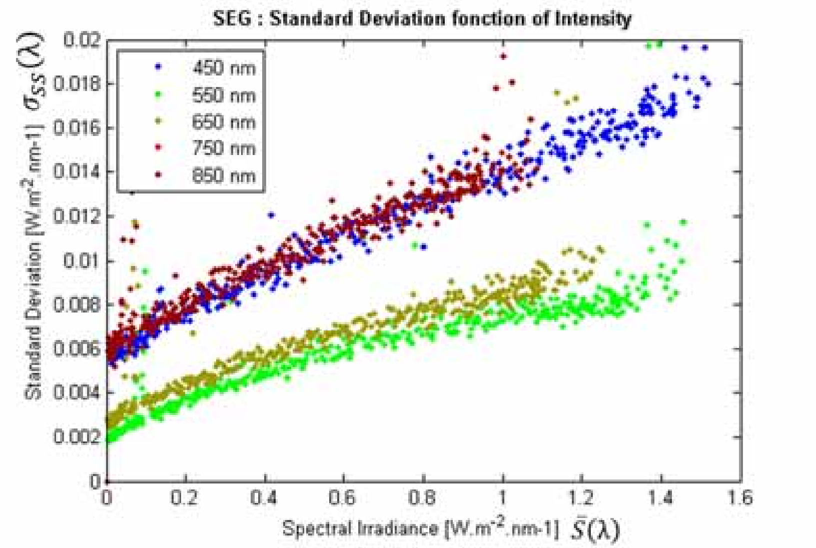


Fig 5: Standard deviation function of mean intensity. For each “one minute acquisition”, we obtain a mean spectrum and a standard deviation spectrum. After hundreds of measurements we can see the behavior for five wavelengths. We can compare these results to the transfer function (Fig 4).

3. Results

The careful study of this installation has shown numerous possible error sources. A strict calibration led to the understanding of the system limitations and allowed to produce for each measurement their own uncertainty and variability. You can see (Fig 6) example of spectrum for two kinds of sky (clear one and cloudy one). The effect of weather variability is clearly identified.

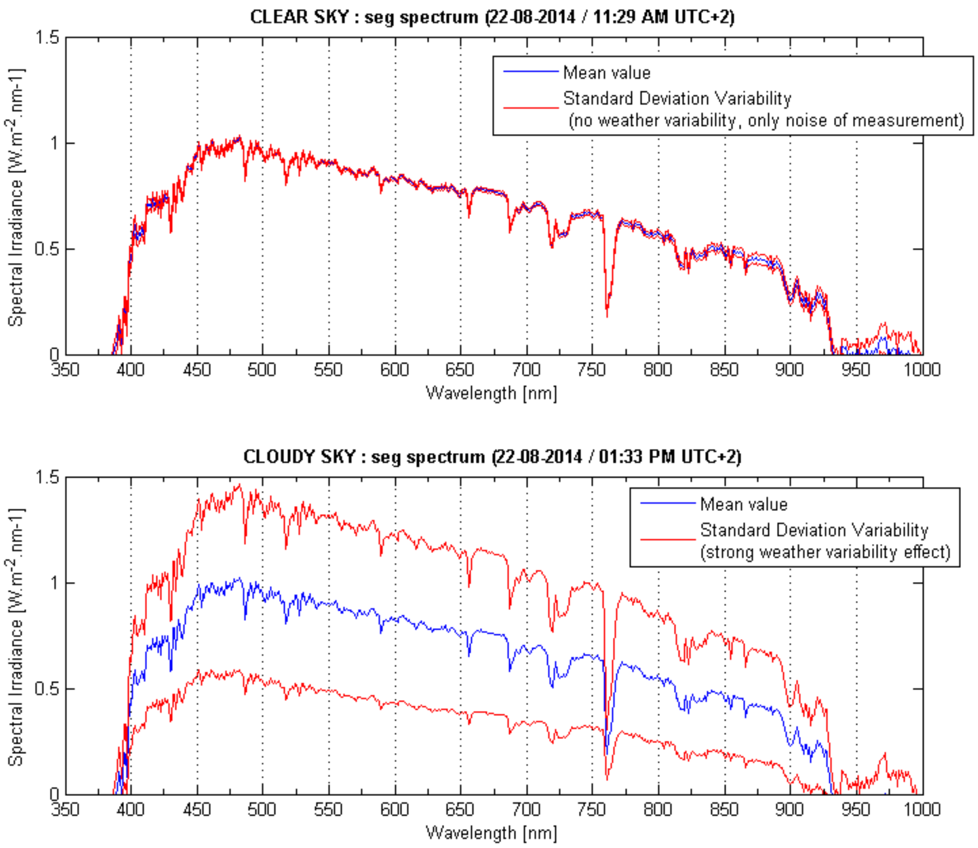


Fig 6: Seg spectrums for clear sky (above) and cloudy conditions (below). We chose on purpose two mean spectrums very similar. In this case, if you take only the mean spectrums into account there is, almost, no way to know weather conditions.

On the next figure (Fig 7), you can see the other kind of measurements, the one second integrated acquisition values. They are presented for August 22nd 2014, the same day where the two spectrums shown in Fig 6 were measured.

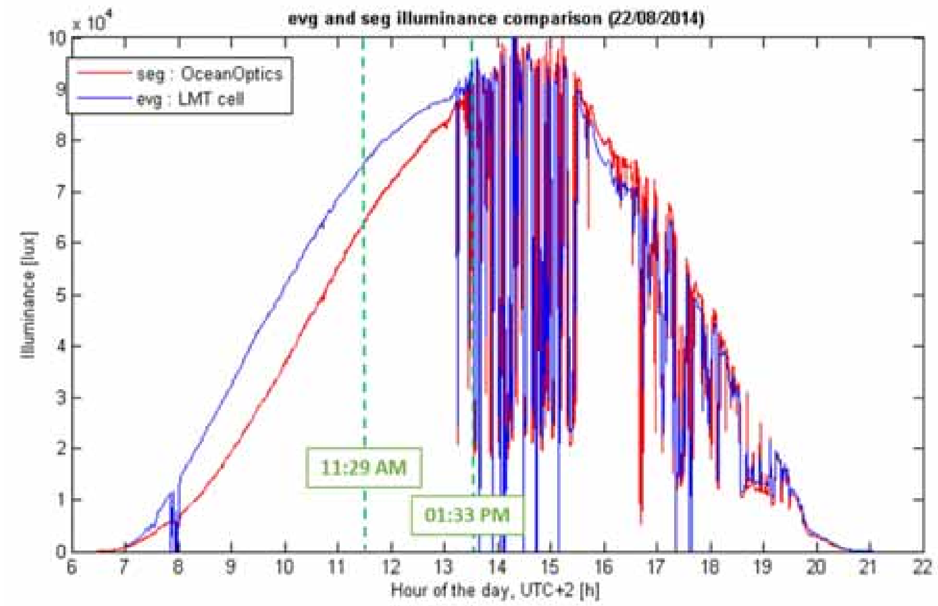


Fig 7: Comparison between our absolute reference: the LMT cell and the illuminance calculated from the Ocean Optics spectroradiometer.

You can notice, the strong difference between evg and seg signal. Under clear sky conditions, the main source of radiation is the sun, a dot of light in the sky, so this difference is mainly due to the very different angular efficiency of the captors. During cloudy sky, the impact of the angular efficiency is less important.

4. Outlook and possible enhancements

Removal of optical fibers

We can see on the spectral transfer function (complete line) that the spectral bandwidth is far narrower than the spectrometer capability (350-1000nm). The OceanOptics lines are almost blind below 400nm and above 800nm. This limitation is mainly due to the spectral transfer of the 15 meters optical fiber. One way of improvement would be the suppression of the optical fiber and the installation of the spectrometers on the station. In our situation, the modifications will be quite heavy.

Relative calibration with a warm source

The relative calibration needs a light source of a blackbody kind. The problem is that it is difficult to find an intense and warm (above 3400K) halogen lamp which would provide a higher flux below 450 nm.

All sky imaging camera HDR coupling

Our next step will consist in installing an all sky HDR camera. By providing a luminance map of the sky under any weather condition, this device will be at the center of the comparison between all our illuminance measurements. By taking into account the angular efficiency of each cell, we will be able to explain and correct the differences observed in Fig 7.

Comparison with local simulations

Once the spectral measurements will be fully available and coupled to the rest of the station, the next step will be to produce modelled spectrums. To do that, we'll use RTM software such as LibRadtran (Mayer and Kylling, 2005) fed by local atmospheric information from air quality stations (Air, 2014).

5. References

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Air Rhône-Alpes Observatory: http://www.air-rhonealpes.fr/