Radiometric calibration of the TreeTalker (TT+) spectrometer

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Rationale

Spectral raw data from the TreeTalker device are output as radiometrically uncalibrated and with the 12 different spectral bands not directly comparable among each other, hence hindering the retrieval of the real spectral signature from the observations. This report describes the methodology and results of experiments aimed at obtaining custom calibration factors to convert the raw data output from the TreeTalker spectrometer into values of radiative energy flux for each spectral band.

Instruments

TreeTalker

The TreeTalker [1, 2] includes a spectrometer based on AMS sensor chips (AS7262, AS7263) located in the upper side of the device and protected by a pyrex glass placed over an aperture hole drilled on top of the plastic case. This configuration is common for all the TreeTalker devices belonging to the TT+ series. For the performance of the tests described in this report a TT+ 3.2 was used.

The AS7262 is a cost-effective multispectral sensor-on-chip solution designed to address spectral ID applications. This highly integrated device delivers 6-channel multispectral sensing in the visible wavelengths from approximately 430 nm to 670 nm with full-width half-max (FWHM) of 40 nm [3]. The AS7263 is a digital 6-channel spectrometer for spectral identification in the near IR (NIR) light wavelengths. AS7263 consists of 6 independent optical filters whose spectral response is defined in the NIR wavelengths from approximately 600 nm to 870 nm with full-width half-max (FWHM) of 20 nm [4]. Specific information on the spectral features of the individual bands is provided in table 2. Both sensor models integrate Gaussian filters into standard complementary metal–oxide–semiconductor (CMOS) silicon via Nano-optic deposited interference filter technology and are packaged in a Land Grid Array (LGA) package that provides a built-in aperture to control the light entering the sensor array. Control and Spectral data access is implemented through either the I²C register set, or with a high level AT Spectral Command set via a serial UART (Universal Asynchronous Receiver-Transmitter).

RS5400 spectroradiometer

The RS-5400 [5], manufactured by Spectral Evolution, is a high resolution/high sensitivity portable spectroradiometer for field use. The RS-5400 has a spectral range of 350-2500 nm and three high-density photodiode array detectors: a 1024 element UV-enhanced Silicon array for 350-1000 nm; a 512 elements Extended indium-gallium-arsenide (InGaAs) photodiode array for 1000-1900 nm, and a 512 element Extended InGaAs photodiode array for 1900-2500 nm. The measurements featured spectral resolution is 2.5, 5.5 and 5.8 nm at 700, 1500 and 2100 nm wavelength respectively. The RS-5400 unit is lightweight and runs off a 100-240V AC power supply or lithium-ion batteries. The RS-5400 is designed for field work with a rugged chassis, no moving optical parts, and rugged metal clad fiber optic cable that's field replaceable. It features one touch operation with auto-dark current and auto-exposure. For the experimental activities described in this report an RS5400 instrument provided with a radiometrically calibrated output was used.

Experiments

The experimental design included indoor and outdoor tests both conducted under conditions of artificially scattered (diffuse) light, except for 1 outdoor test with the sensors pointed in vertical position towards the clear sky aimed at verifying the consistency of calibration factors under the condition of natural light scattering (table 1). During all the performed tests, paired measurements were taken with the optics of the two instruments at the closest possible distance resulting in about 2 cm distance between their respective centers.

Indoor tests were performed in laboratory under different light levels obtained by covering the sensors optics with additional layers of translucent white polystyrene homopolymer (PET) filters.

In the case of indoor tests, the TreeTalker and the RS5400 spectroradiometer connected to an optical fiber were kept standing vertically in mid position under two artificial 1000 W light sources (OSRAM 64575 halogen lamp) each pointed upwards against reflective umbrellas (figure 1).

For each distinct light level experiment data consisted in at least 5 replicates from each instrument with the TT being operated in test mode and checked on a pc via serial connection (Arduino IDE serial monitor) and the RS5400 readings taken manually and triggered simultaneously to the TT spectral data acquisition.

Indoor tests were performed on 8th August 2022 in the forest ecology laboratory at Edmund Mach Foundation premises under at ambient temperature between 28.3 and 28.6 °C.

Outdoor tests were performed on 9th August 2022 in a parking lot out of the laboratory of the Edmund Mach Foundation with clear sky conditions between 10:30 and 11:00 CET with sun elevation between 43.2 and 48.2 degrees. Air temperature measured at the nearest weather station (Maso delle Part weather station

#T0408 meteotrentino.it, distance 2300 m from test site, same altitude on the Rotaliana plain) during the tests ranged from 27.1 to 27.5 °C.

Experiments consisted in 2 trials under artificially scattered sunlight and 1 under sky scattered sunlight. For each experiment 5 measurements were taken with each spectrometer.

The TreeTalker and the RS5400 optical fiber were positioned with the same configuration of indoor experiments but both oriented either upwards (zenith) or downward (nadir) depending on the experiment type. When pointing towards the zenith the limited optical field of view of the TT sensor chips (±20°) and of the RS5400 optical fiber (±12.5°) prevented the spectrometers from targeting the sun thus receiving direct sunlight. Under such configuration two tests were run respectively with and without the application of a PET light diffusing filter on top of the TT spectrometer lens. When the instruments were pointed towards the nadir they received the light scattered by a highly reflective Spectralon panel with Lambertian reflectance from 250 to 2500 nm. The square reflectance target with a side of 61 cm was positioned under the spectrometers avoiding any shadowing and at an appropriate distance to exclude any other element than the panel itself from the spectrometers field of view. The Spectralon Diffuse Reflectance target offers diffuse reflectance value of 99% of any known substance. and is spectrally flat over the UV-VIS-NIR spectrum.

During the data collection the TT spectrometer was configured with a gain factor of 2 (16x) and 3 (64x) for outdoor and indoor use respectively; the whole dataset was then harmonized to a common gain factor (2) for the purpose of comparing the results of the different sets of experiments.

Calculation method.

The radiometric readings output from the RS5400 spectrometer, that are dimensionally expressed as energy flux per unit wavelength and unit solid angle [W m^{-2} sr^{-1} nm^{-1}], are first considered to calculate the energy flux relative to the 20° field of view of the AMS sensor chips.

In this respect it should be recalled that the solid angle (Ω) of a cone with its apex at the apex of the solid angle, is the area of a spherical cap on a unit sphere. Let the apex angle be equal to 2θ (fig. 2), then Ω will be:

$$\Omega = 2\pi(1 - cos\theta) = 4\pi sin^2\left(\frac{\theta}{2}\right) \qquad [sr]$$

Accordingly, the radiative energy per single wavelength k relative to field of view (E_{FOV}) of a given instrument is calculated as follows:

$$E_{FOV}(k) = E(k) \cdot \Omega \qquad [Wm^{-2}nm^{-1}]$$

Where E(k) is the radiative energy flux per unit solid angle [W m^{-2} nm^{-1} sr^{-1}] for each measured wavelength k

In the specific case of AMS sensor chips the resulting EFOV of the TreeTalker spectrometer will thus be:

$$E_{FOV}(k) = E(k) \cdot 4\pi sin^2\left(\frac{20}{2}\right) \qquad [Wm^{-2}nm^{-1}]$$

Where E is the radiative energy flux per unit solid angle [W m^{-2} sr^{-1} nm^{-1}], measured by the RS5400 spectroradiometer.

The radiative energy of each band *i* of the TreeTalker spectrometer (E_{FOV}(i)) can then be calculated by integrating the product of the measured radiative energy and the spectral responsivity function across the range between 350 and 1075 nm (fig 5, 6) according to:

$$E_{FOV}(i) = \int_{k=350}^{1075} E_{FOV}(k) \cdot R(i,k) \qquad [Wm^{-2}]$$

Where R(i,k) is the value of the responsivity function estimated for each of the i bands of the AMS sensor chips at each wavelength k.

Responsivity functions

In electronics and signal processing, mainly in digital signal processing, a Gaussian filter is a filter whose impulse response is a Gaussian function (or an approximation to it since a true Gaussian response would have infinite impulse response). The instrumental response of spectrometers is ordinarily parameterized by using indeed gaussian type functions [5, 6, 7].

In the specific case of the AMS sensor chips the gaussian function was fitted for each band i considering the band responsivity peak and the full width half maximum (FWHM) from the sensors' datasheet (table 2) constraining the parameters m (band mean wavelength, coinciding with the function peak) and σ (standard deviation) in the following general equation:

$$\mathrm{R(k)} = \frac{1}{\sqrt{2 \cdot \pi \cdot \sigma}} \cdot e^{-\frac{1}{2}\left(\frac{k-m}{\sigma}\right)^2}$$

The parameterization resulted in σ values of 17 and 8.5 for the AS7262 and AS7263 bands respectively, while m was equal to the band peak values reported by the sensors manufacturer (fig 3, 4).

Calibration factors

Calibration factors (CF) for each band i are generically calculated by relating the adimensional output of the TreeTalker spectrometer (DN) expressed as digital number to the measured radiative energy flux (E_{FOV}) and expressed in physical units, according to:

$$CF(i) = DN(i) / E_{FOV}(i)$$

Three different quantitative approaches were however used in determining the amount of radiative energy of each band, that led to a corresponding set of calibration factors.

a) Energy flux limited to the midband wavelength (band peak). In the theoretical case of a light source with a uniformly distributed energy spectra across the wavelengths range, this metric allows to convert the TreeTalker spectrometer raw output into radiometrically calibrated energy relative to the mid wavelength of each band.

$$CF_{band\_peak}(i) = DN(i) / E_{FOV\_band\_peak}(i)$$

b) Band width power: energy flux E_{FOV} is integrated across a range equal to the double of the FWHM. The integration range is therefore ±40 and ±80 nm for the AS7263 and AS7262 sensor chips respectively and corresponds to 98.5% of the total energy sensed by the sensor under each band. Because of the different bands amplitude between the two sensor models, this metric cannot be used to directly retrieve a correct spectral signature from the sensed target.

$$CF_{band\_width}(i) = DN(i) / E_{FOV\_band\_width}(i)$$

c) Bandwidth power per unit wavelength. This metric is retrieved by the normalization of the energy flux under each band, illustrated at point b, by its wavelength integration range (int_{width}) and it yields a realistic spectral signature of the sensed target.

$$CF_{band\_width\_norm}(i) = DN(i) / [E_{FOV\_band\_width}(i) \, / \, (int_{width})]$$

An example of the application of the calibration factors for the various bands to TT+ data collected outdoor and the resulting spectral pattern is given in fig. 7.

Results and Discussion

The calibration factors resulting from the application of the three different metrics are reported in tables 3, 4 and 5.

The comparison of the factors relative to the full bandwidth energy, either normalized per the wavelength range and not, obtained from the different tests show an overall good agreement for all the bands with central wavelength larger than and including 600 nm. These include all the 6 bands of the AS7263 sensor chip and the 2 of the AS6272 at the longest wavelength which featured a coefficient of variation (CV) among tests between 2.3% and 8.1% irrespectively of the chosen metric to express the calibration factors. Bands centered at 550 and 570 nm exhibited somewhat larger CV values between 9.2% and 10.7%, while the behavior of the bands with at peaks lower wavelengths were remarkably variable across tests, with CV values of 14.5% (500 nm) and 22.5% (450 nm).

The observed coefficients variability for some of the bands (450, 600, 610 ,730, 810, 860 nm) depended primarily on the difference of the coefficients retrieved from two sets of indoor/outdoor experiments, since the coefficient of variation of the lab trials alone was in this case significantly smaller than the overall variability of the complete dataset. For the remaining bands (500, 550, 570, 680, 650, 760 nm) the calibration factors variability within the lab dataset alone was in line with the ensemble dataset statistics.

The calibration factors relative to the bands' energy peaks confirm the limited variability among the performed tests. However, the band centered at 760 nm features a large variability (CV: 32.3%) due to the distinct and characteristic spectral signature of the sun light compared to that produced by the halogen lamp. The latter is characterized by a deep in the 760 nm range, therefore the energy of the band peak deviates sensibly from the mean energy per unit wavelength of the other sensed wavelengths of each band. On the contrary the halogen light spectrum presents a more uniform distribution of the energy flux through all the wavelength of the band. These results suggest that the peak of a given band's energy flux will be associated to a considerable and increasing error the more the energy flux is variable within its wavelength sensing range.

Calibration coefficients reported in tables 3-5 do not include results from the outdoor test carried out with the spectrometers targeting sky without diffusing filter (tab. 1 exp. VII); this particular test result indeed in remarkably much larger ratios, from +35% to +787% and an average increase of +293%, between the TT+ bands digital output and their independently measured energy fluxes compared to what observed in the other experimental conditions (fig.8). This result can be attributed to several reasons, such as: i) the difference in the field of view of the two instruments; ii) the impact of straylight on the measurements of the TT+; iii) the absence of a light diffuser. Although the sun position during the measurements was not viewed by the sensors and the test was performed on a clear sky day, the targeted sky sectors can hardly be homogeneous in terms of diffuse solar irradiance; furthermore some of the direct sunlight beams may reach the TT+ detector after being refracted or reflected by the mirror and the rim of the hole on the plastic case through which the light reaches the AMS sensor chips. Finally, the lack of a diffusing filter above the sensors which conveys and diffuses the light from wider angles than the respective FOV, contributes to enhance the difference in the amount of sensed radiation when spectral irradiance of the sky, or any other target, is inhomogeneous.

References:

[1] Valentini, R.; Belelli Marchesini, L.; Gianelle, D.; Sala, G.; Yarovslavtsev, A.; Vasenev, V.; Castaldi, S. New tree monitoring systems: From Industry 4.0 to Nature 4.0. Ann. Silvic. Res. 2019, 43, 84–88.

[2] Matasov, V.; Belelli Marchesini, L.; Yaroslavtsev, A.; Sala, G.; Fareeva, O.; Seregin, I.; Castaldi, S.; Vasenev, V.; Valentini, R. IoT Monitoring of Urban Tree Ecosystem Services: Possibilities and Challenges. Forests 2020, 11, 775. https://doi.org/10.3390/f11070775

[2] AMS as 7262/7263 datasheet. AS7262 Spectral Sensing Engine. ams. url: https ://ams.com/en/as7262

[3] AMS as 7262/7263 datasheet. AS7263 Spectral Sensing Engine. ams. url: https ://ams.com/en/as7263

[4] RS5400 spectrometer datasheet. https://spectralevolution.com/products/hardware/compact-lab-spectroradiometers/rs-5400-spectroradiometer/

[5] Beirle, S., Lampel, J., Lerot, C., Sihler, H., and Wagner, T.: Parameterizing the instrumental spectral response function and its changes by a super-Gaussian and its derivatives, Atmos. Meas. Tech., 10, 581–598, https://doi.org/10.5194/amt-10-581-2017, 2017

[6] Todd B. Sauke, Joseph F. Becker (2005). Modeling, measuring, and minimizing the instrument response function of a tunable diode laser spectrometer, Journal of Quantitative Spectroscopy and Radiative Transfer, Volume 91, Issue 4, 453-484, https://doi.org/10.1016/j.jqsrt.2004.07.005.

[7] Mihai, L.; Mac Arthur, A.; Hueni, A.; Robinson, I.; Sporea, D. Optimized Spectrometers Characterization Procedure for Near Ground Support of ESA FLEX Observations: Part 1 Spectral Calibration and Characterisation. Remote Sens. 2018, 10, 289. https://doi.org/10.3390/rs10020289.

[8] Wikipedia contributors. (2023, October 4). Solid angle. In Wikipedia, The Free Encyclopedia. Retrieved 15:27, October 25, 2023, from https://en.wikipedia.org/w/index.php?title=Solid_angle&oldid=1178548334

Tables

Conditions	Experiments						
	I	II	III	IV	V	VI	VII
Indoor	■	■	■	■			
Outdoor					■	■	■
Artificial light (halogen lamp)	■	■	■	■			
Sun light					■	■	■
PET Filter (*)		■ 1x	■ 2x	■ 3x		■ 1x	
Diffuse reflectance panel					■		

(*) indicates if diffuser filter is used and number of layers applied.

Table 1. Tests synoptic scheme

sensor chip model	**band peak (nm)**	FWHM (nm)	wavelength accuracy (nm)
AS 7262	**450**	40	5
	500	40	5
	550	40	5
	570	40	5
	600	40	5
	650	40	5
AS 7263	**610**	20	5
	680	20	5
	730	20	5
	760	20	5
	810	20	5
	860	20	5

Table 2. Spectral response features of the sensor chips assembled in the TreeTalker spectrometer. FWHM stands for Full Width Half Maximum.

band (nm)	lab no filter	lab filter x1	lab filter x2	lab filter x3	outdoor up filterx1	outdoor down panel	**mean**	**st.dev**	**CV%**
450	1081.6	1279.2	1398.8	1473.2	867.1	766.0	**1144.3**	288.1	25.2
500	866.8	1136.5	1202.3	1230.4	1005.7	902.9	**1057.4**	154.9	14.7
550	799.3	937.9	980.5	998.2	867.3	801.4	**897.4**	87.7	9.8
570	737.3	931.6	974.4	990.5	897.5	828.0	**893.2**	96.0	10.7
600	843.0	835.9	864.2	873.9	847.2	791.4	**842.6**	28.8	3.4
650	744.5	812.4	836.0	841.8	867.4	802.9	**817.5**	42.4	5.2
610	527.9	511.3	522.1	526.5	536.5	485.5	**518.3**	18.0	3.5
680	437.7	519.6	530.4	536.0	513.7	460.2	**499.6**	40.6	8.1
730	478.2	482.3	491.0	494.5	565.9	527.4	**506.5**	33.9	6.7
760	427.0	470.3	478.9	482.6	807.6	850.0	**586.1**	189.5	32.3
810	516.5	505.1	512.4	515.1	539.4	508.7	**516.2**	12.1	2.3
860	490.8	498.1	503.7	505.5	578.4	526.1	**517.1**	32.3	6.2

Table 3. Calibration factors resulting from the different tests and ensemble statistics. Energy relative to band peak (CF_{band_peak}). Units: 1/[10^{-6}*W cm^{-2}]

band (nm)	lab no filter	lab filter x1	lab filter x2	lab filter x3	outdoor up filterx1	outdoor down panel	**mean**	**st.dev**	**CV%**
450	25.3	29.9	32.7	34.5	21.4	19.5	**27.2**	6.1	22.5
500	20.3	26.4	28.0	28.6	23.5	21.0	**24.6**	3.6	14.5
550	18.7	22.0	22.9	23.3	20.6	19.1	**21.1**	1.9	9.2
570	17.3	21.8	22.8	23.2	20.7	19.0	**20.8**	2.3	11.0
600	19.8	19.6	20.3	20.5	19.8	18.6	**19.8**	0.7	3.4
650	17.4	18.9	19.5	19.6	20.0	18.5	**19.0**	0.9	4.9
610	24.8	24.0	24.5	24.7	25.3	22.9	**24.4**	0.8	3.5
680	20.4	24.2	24.7	24.9	24.9	22.3	**23.6**	1.8	7.7
730	22.4	22.7	23.1	23.3	24.8	23.1	**23.2**	0.8	3.6
760	20.0	22.0	22.4	22.6	25.0	23.1	**22.5**	1.6	7.2
810	24.2	23.7	24.0	24.1	26.7	25.2	**24.6**	1.1	4.6
860	23.0	23.4	23.7	23.9	27.7	25.2	**24.5**	1.8	7.2

Table 4. Calibration factors resulting from the different tests and ensemble statistics. Energy relative to full bandwidth (CF_{band_width}). Units: 1/[10^{-6}*W cm^{-2}]

band (nm)	lab no filter	lab filter x1	lab filter x2	lab filter x3	outdoor up filterx1	outdoor down panel	**mean**	**st.dev**	**CV%**
450	2060.5	2428.3	2660.7	2808.0	1742.7	1587.1	**2214.6**	497.4	22.5
500	1648.0	2149.3	2276.0	2323.6	1910.4	1708.8	**2002.7**	289.8	14.5
550	1523.2	1784.9	1864.3	1895.1	1674.9	1550.0	**1715.4**	158.3	9.2
570	1404.0	1772.6	1852.8	1884.1	1683.4	1548.6	**1690.9**	185.9	11.0
600	1609.8	1595.4	1647.1	1664.4	1608.7	1509.5	**1605.8**	53.9	3.4
650	1413.0	1538.4	1581.8	1593.3	1623.5	1501.7	**1542.0**	76.3	4.9
610	1007.6	974.1	994.5	1003.2	1026.6	928.7	**989.1**	34.2	3.5
680	829.9	982.6	1001.9	1011.4	1011.6	905.1	**957.1**	74.1	7.7
730	911.6	920.6	937.4	944.8	1008.4	936.6	**943.2**	34.2	3.6
760	812.4	895.4	911.3	918.1	1015.7	938.1	**915.2**	65.7	7.2
810	982.7	961.6	974.6	980.0	1084.6	1022.1	**1000.9**	45.8	4.6
860	934.1	949.9	962.5	968.7	1126.3	1024.0	**994.3**	71.5	7.2

Table 5. Calibration factors resulting from the different tests and ensemble statistics. Energy relative full bandwidth per unit wavelength peak ($CF_{band\_peak\_norm}$). Units: 1/[10^{-6}*W cm^{-2} nm^{-1}]

Figures

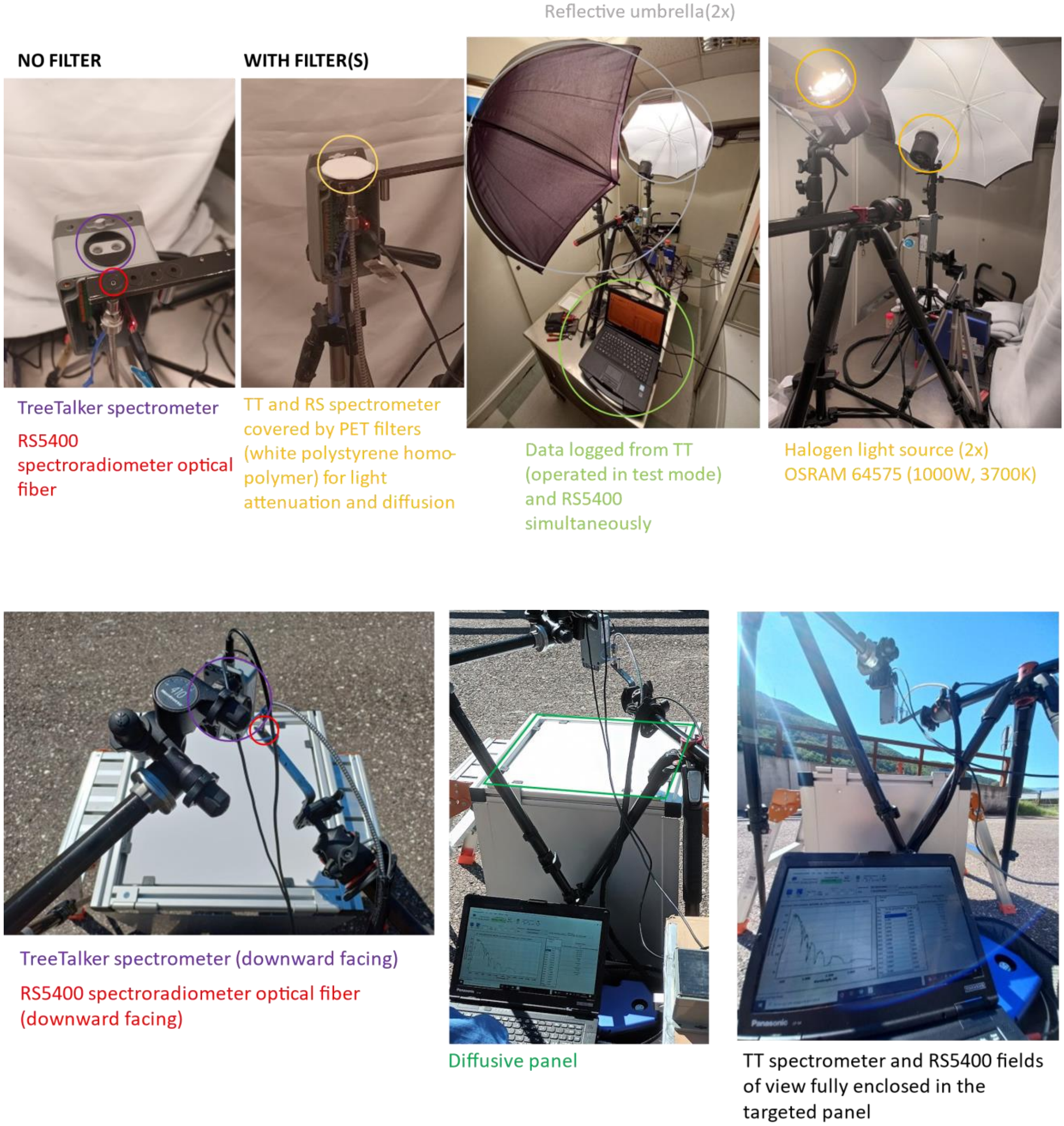

Figure 1. Overview of laboratory and outdoor tests instrumental set up. Outdoor testing included positioning the spectrometer upwards to view the sky (not shown in the photos) with the same set-up of indoor experiments but the light source.

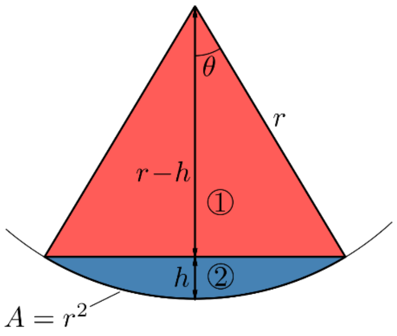

Fig 2. Section of cone (1) and spherical cap (2) inside a sphere. In this figure Ω = 1 and r = 1. Original figure from [8].

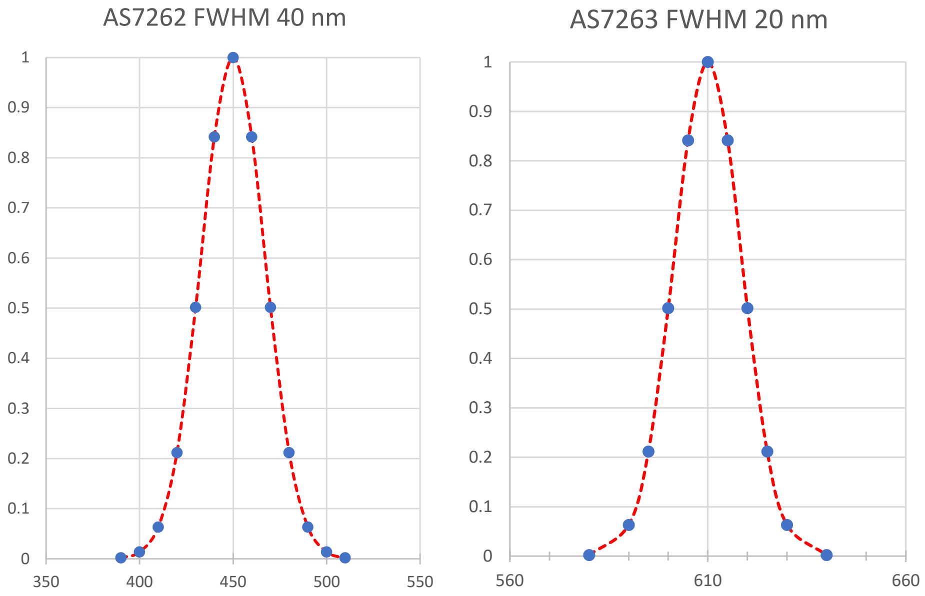

Figure 3. Responsivity of AS7262 (left) and AS7263 (right) sensor chips, exemplified by one band respectively, obtained by fitting the spectral response data in the technical specifications with a gaussian function. Band standard deviation (σ)= 17(AS7262); 8.5 (AS7263); band mean (m)= 450 (AS7262); 610 (AS7263). X axis: wavelength (nm). Y axis: energy flux fraction relative to band peak.

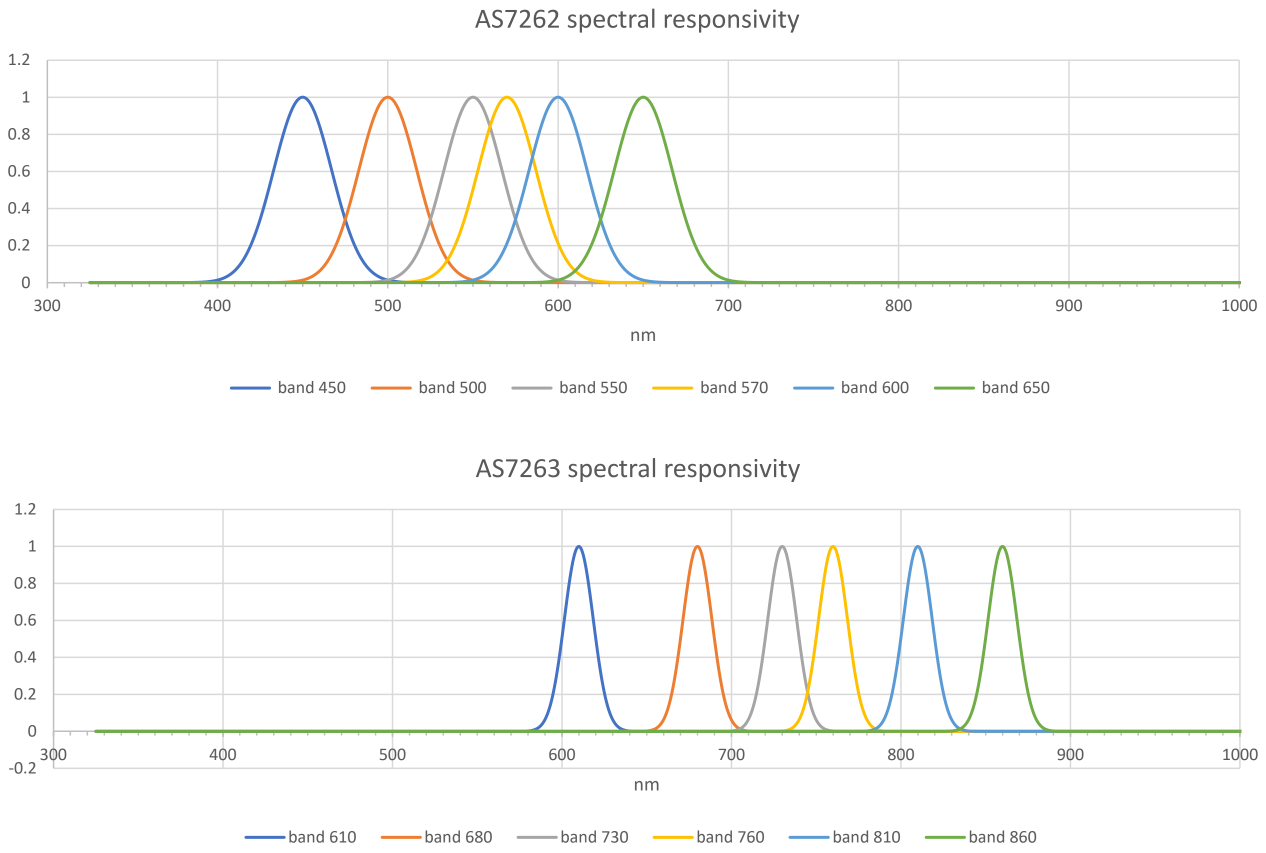

Figure 4. Ensemble view of the AS7262 (top) and AS7263 (bottom) bands spectral responsivity; note the band amplitude difference between the two models. X axis: wavelength (nm). Y axis: energy flux fraction relative to band peak.

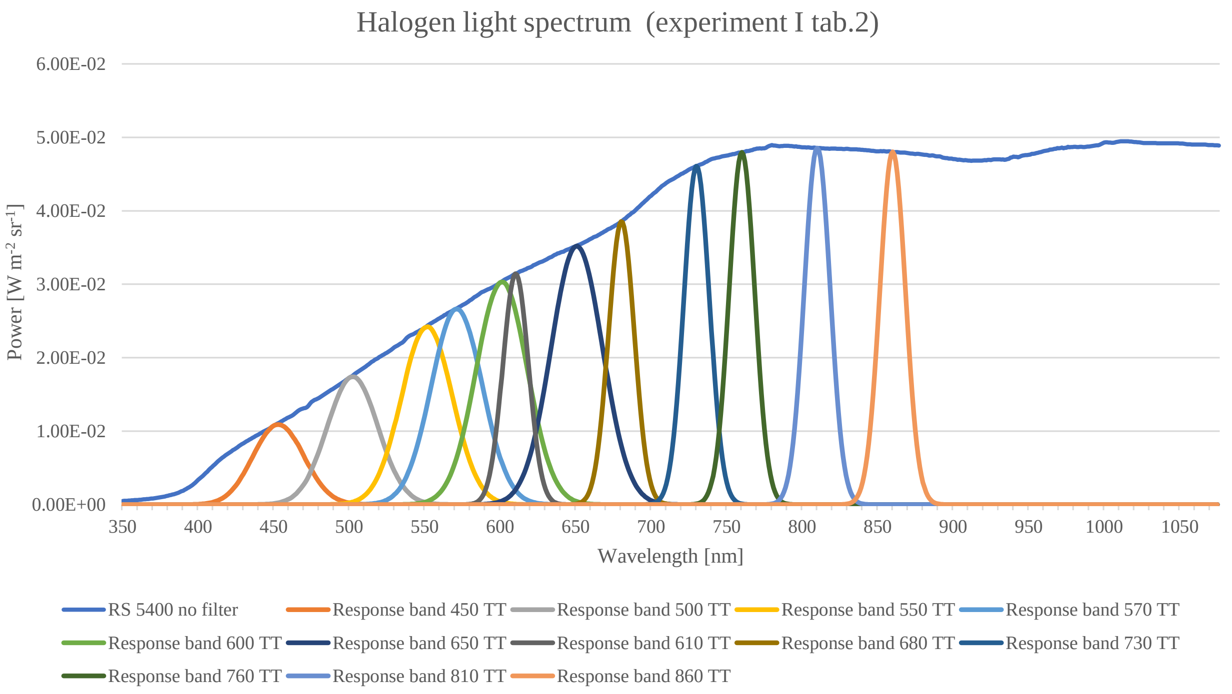

Figure 5. Spectrum of the artificial light used for indoor experiment measured by the RS5400 spectroradiometer and estimated response of TreeTalker spectrometer for each band.

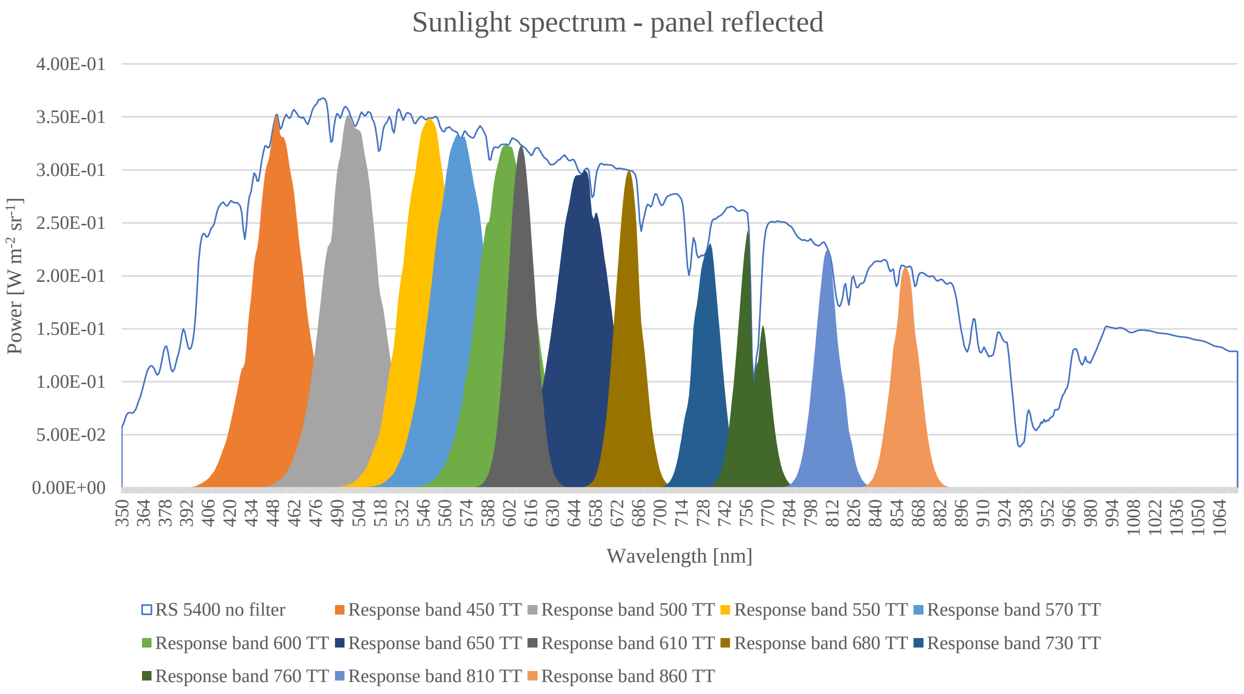

Figure 6. Example of spectrum of sun light during outdoor experiments measured by the RS5400 spectroradiometer and estimated response of TreeTalker spectrometer for each band.

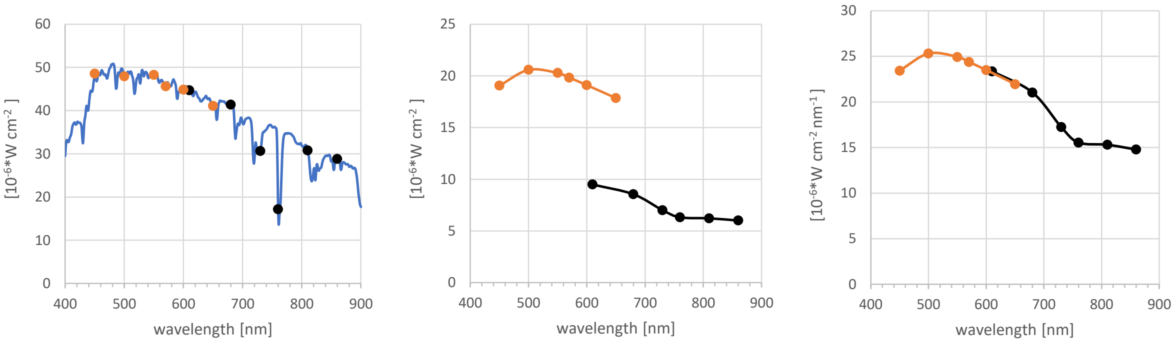

Figure 7. Example of estimated energy flux after application of calibration factors to TreeTalker raw output. Band peak energy compared to continuous sun radiation energy spectrum independently measured by RS5400 (left); band width energy (middle); bandwidth per unit wavelength (right). Note the different scale of the y axis.

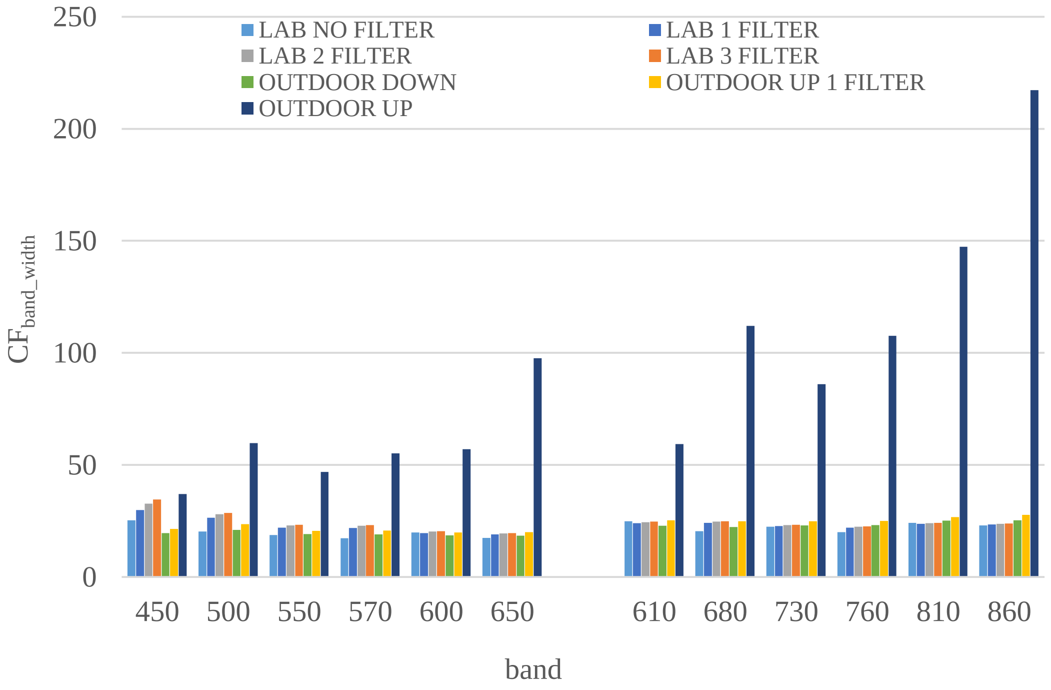

Figure 8. Comparison of calibration coefficients for full band energy (CF_{band_width}) obtained from the various tests in artificially diffused light conditions, both indoor and outdoor, and targeting the sky without using a PET filter or a diffusive panel (OUTDOOR UP series).