Uncertainties in Photosynthetically Active Radiation (PAR) Experimental Data Collected in Brazil and Spain

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Abstract

Photosynthetically Active Radiation (PAR) plays a critical role in evaluating agricultural productivity and ecosystem dynamics. Despite its importance, ground-based radiometric measurements of PAR are limited and often exhibit large uncertainties due to sensor degradation and calibration issues. Consequently, PAR is frequently estimated as a fixed fraction (typically 42–52%) of global horizontal irradiance (GHI), both in ground-based and satellite-derived datasets. This approach may introduce bias besides omitting the spatial and temporal variability of PAR fractions. This study is part of a collaborative effort between Brazil and Spain to investigate uncertainties in PAR measurements and satellite products. The methods depart from field campaigns by comparing long-term radiometric stations to a more accurate and calibrated rotating shadow-band spectroradiometer. Three field campaigns were accomplished at Spain while Brazilian field campaigns will take place during 2025/2026 season. Preliminary results points that conventional PAR sensors induced bias in PAR/GHI fraction varying from +6% to -12% for a monthly average. Temporal variability showed minimal differences. The variability of PAR fraction on the direct and diffuse components was also assessed showing values for diffuse spectra around 0.54 while 0.43 for direct. However, variability of PAR fraction for diffuse is much larger ranging from 0.3 to 0.8 for the 5th to 95th percentiles. These results emphasize the need of a cautious verification on PAR sensor biases prior to scientific use, as well provide more details on PAR variability for direct and diffuse components.

Keywords: photosynthetically active radiation, radiometry, instruments

1. Introduction

The portion of electromagnetic radiation in the visible spectrum (400 to 700 nanometers) used by plants and algae to perform photosynthesis is defined as Photosynthetically active radiation (PAR). It is typically measured in terms of micromoles of photons per square meter per second (μmol/m².s) and indicates the energy flux per area that reaches the Earth's surface with the potential to perform photosynthesis. Measuring PAR radiation is essential for estimating agricultural productivity, biomass production, and supporting ecological studies. Radiometric measurements of PAR at the surface are scarce, and the conventional sensors show high uncertainties (~10% according to Su et al., 2007) and unknown degradation. Better quality measurements based on spectroradiometers are rare. On the other hand, PAR radiation has a robust correlation with global solar radiation (GHI) and is commonly estimated through empirical fractions that range from 42% to 52% (Escobedo et al., 2014; Yu et al., 2015; Ferrera-Cobos et al., 2020) on a monthly scale. Satellite estimates are no different, although many radiative transfer models can estimate atmospheric attenuation for different ranges of the spectrum (Dye, 2004; Casagrande et al., 2021), their performance for the PAR range is unknown, especially in conditions of variable cloudiness, typical of tropical climates (Tan and Ismail, 2016). For this reason, many satellite estimates end up adopting constant empirical fractions, which may be not very representative of the temporal and spatial variability for the Brazilian territory.

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Conventional PAR sensors are basic silicon photodiodes combined with a spectral filter producing a current signal proportional to light intensity. A shunt resistor converts it to voltage outputs calibrated to μmol/s.m². Filter design and photodiode accuracy contributes largely to measurements uncertainty. More accurate measurements usually rely on grating spectroradiometers, that despite being based also on photodiode sensors allow wavelength-dependent calibration, improving accuracy. Literature provides some validation studies on PAR estimates from spectral sensors onboard satellites (Senna et al., 2005) but lack more accurate PAR studies based on filed measurements with this type of sensors (Su et al., 2007). Other studies have evaluated these fractions from experimental data, demonstrating their dependence on solar geometry, aerosol concentrations, water vapor, and cloudiness in the atmosphere (Wang et al., 2014).

The variability of the PAR/GHI fraction is poorly studied in Brazil. Custodio et al. (2021) evaluated this fraction for two stations of the Sonda/INPE Network, showing a large variation in the PAR/GHI fraction, which ranged from 44% in Brasília to 50% in Petrolina. Escobedo et al. (2014) reported PAR/GHI values between 50.7% and 48.2% for Botucatu between the wet and dry seasons. An increase in the PAR/GHI fraction with the zenith angle and cloud cover has been recurrently reported as a consequence of a greater attenuation of the UV and IR spectra by water vapor in the atmosphere.

The absence of validated satellite PAR products can introduce significant deviations in the analyses contained in agrometeorological or biosphere-atmosphere interaction models. This is a relevant challenge for a country of continental dimensions like Brazil, due to its importance as large agri-exporter and provider of ecosystem services at a global level. The aim of this study is to identify appropriate criteria for qualifying PAR measurements by investigating degradation and uncertainties through comparisons between different sensor manufacturers and models using traceable spectral instruments. Thus, to produce a reliable observational PAR database that can be used to validate models or empirical studies related to PAR radiation in Brazil and Spain. This work aims to evaluate the uncertainties in the measurements of PAR radiation and its PAR/GHI fraction from experimental campaigns with a calibrated spectroradiometer, comparing them with long-term measurements at these locations.

2. Data and Methods

The EKO MS-711 RSB spectroradiometer provides global and difuse spectral irradiance in the range of 300-1100 nm with 7nm wavelength resolution (Figure 1). The shading mechanism allows the calculation of beam spectral irradiance. Beyond the spectral response of each sensor, these components help to investigate uneven attenuation for the diffuse PAR component. All measurements are taken at 1-minute intervals and PAR irradiance was integrated in the range of 400 nm to 700 nm.

Figure 1: EKO MS-711 RSB spectroradiometer installed at Ciemat (Madrid).

This rotating shadowband spectroradiometer (EKO MS711 RSB) with traceable calibration was used for intercomparisons with long-term stations holding measurements of PAR and global solar irradiance G, summing 5 stations in Brazil and 3 stations in Spain. The spectroradiometer was calibrated with reference data during the ISRC (International Spectroradiometer Intercomparison) experiment carried out by EC/JRC in Ispra (Italy) from 06/09 to 06/13/2025. This sensor provides spectral irradiance data for the global, direct and diffuse components in the range from 300 nm to 1100 nm (Po et al., 2018). Three experimental campaigns were carried out collecting data every 1 minute co-located with the solarimetric stations operated by the Solar Radiation Group of CIEMAT, as shown in Table 1. These stations holds distinct types of sensors as exposed in Table 1.

Table. 1: List of stations and sensors defined for intercomparisons field campaigns.

Station	Country	Broadband sensors	PAR sensors
Petrolina (PTR)	Brazil	K&Z CM22, CHP1	K&Z PQS1, PAR Lite
Brasilia (BRB)	Brazil	K&Z CM22, CHP1	K&Z PQS1, PAR Lite
Cachoeira Paulista (CPA)	Brazil	K&Z CM22, CHP1	K&Z PQS1
Santarém (STM)	Brazil	K&Z CMP10, CHP1	K&Z PQS1
S. M. da Serra (SMS)	Brazil	K&Z CM22, CHP1	K&Z PQS1, PAR Lite
Madrid (MAD)	Spain	Hukseflux SR20	Apogee SQ-500, EKO ML020P
Soria (CED)	Spain	Hukseflux SR20	EKO ML020P
Almería (PSA)	Spain	K&Z CM21/CHP1	EKO ML020P

The spectral response from MS711 was firstly compared to reference sensor for more than 400 measurement samples during a clear-sky day in the ISRC experiment. Deviations from reference was used to correct MS711 spectral irradiance response as shown in Figure 2. These corrections remained within a 5% threshold.

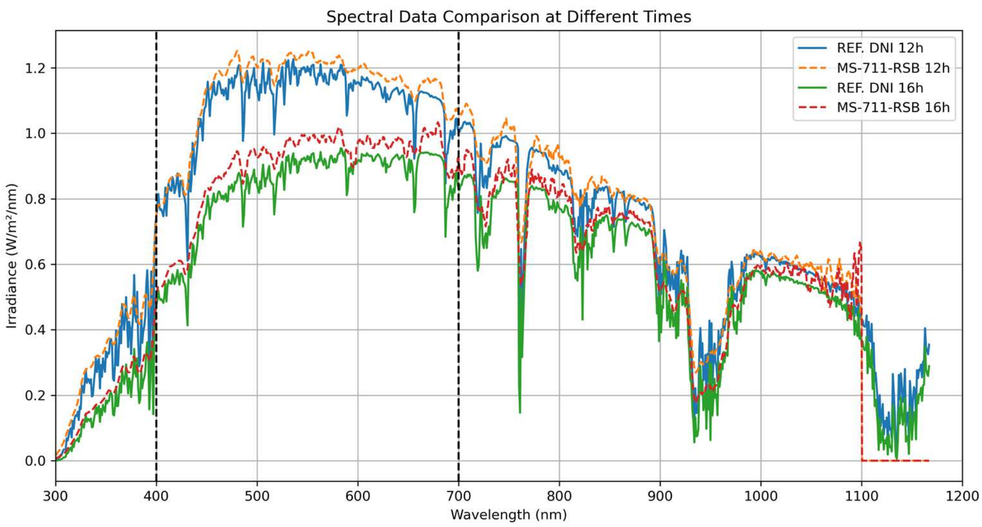

Figure 2: Spectroradiometer signal deviations from reference sensors in ISRC experiment.

Data from the MS711 spectroradiometer were numerically integrated for the PAR range (400 nm to 700 nm) and for the full sensor range (300 nm to 1100 nm). An empirical correction was applied to account for out-of-range irradiance, corresponding to the UV and near-infrared (NIR) (Figure 3) to produce a corresponding GHI output.

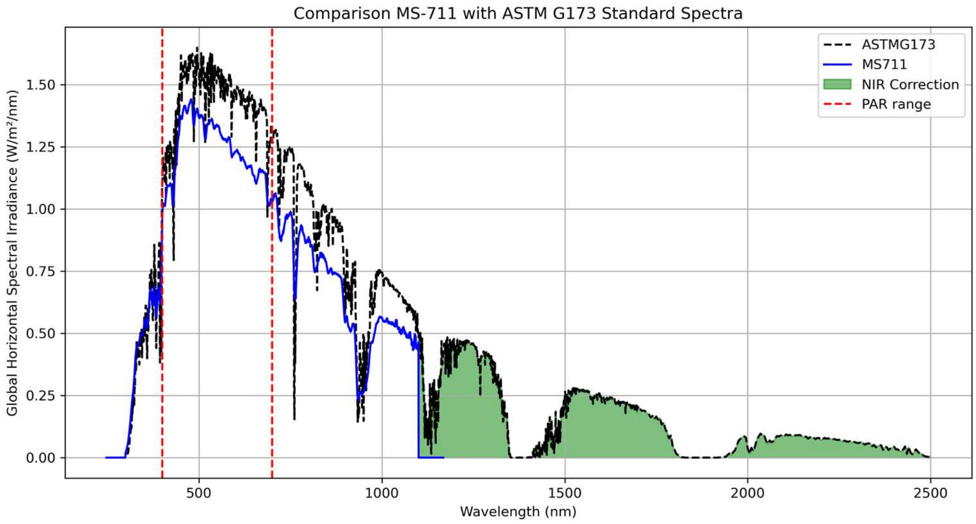

Figure 3: MS-711 spectroradiometer measurement range and NIR correction for GHI estimates.

Diffuse fraction estimated by MS-711 RSB according to Eq. 1 was validated against the one measured by tracker mounted thermopile pyranometers Operational and experimental measurements were synchronized at 1-minute resolution, and PAR/GHI fractions were calculated according to Eq. 2. Whenever possible, PAR and GHI measured by the same sensor were used, allowing for the isolation of differences between sensors. Samples corresponding to zenith angles greater than 75º were discarded to avoid fractions with high angular error. All variables were analyzed in the irradiance unit W/m², with PAR measurements converted from micromoles/m².s to W/m² using a theoretical factor of 0.219 (Thimijan; Heins, 1983).

For estimating the uncertainties in PAR measurements, a spectroradiometer is installed alongside the set of PAR sensors, in order to perform intercomparisons and empirically assess the accuracy of conventional sensors. PAR fractions are obtained according to eq. 1. Finally, measured spectral data will be analyzed for specific sky conditions to identify whether there are bias in the selective spectral attenuation.

$$K_d = \frac{DHI}{GHI} \qquad \text{(eq. 1)}$$

$$F_{PAR} = \frac{PAR}{GHI} \qquad \text{(eq. 2)}$$

3. Results

Figure 4 shows the validation of diffuse fraction estimated from MS-711 RSB against a tracker mounted Class A sensor. We note that despite the high correlation, some dispersion occurs mostly due to non-synchronous and single minute sample from MS-711 RSB procedure while broadband sensors rely on simultaneous global and diffuse measurements averaged along 1-minute intervals.

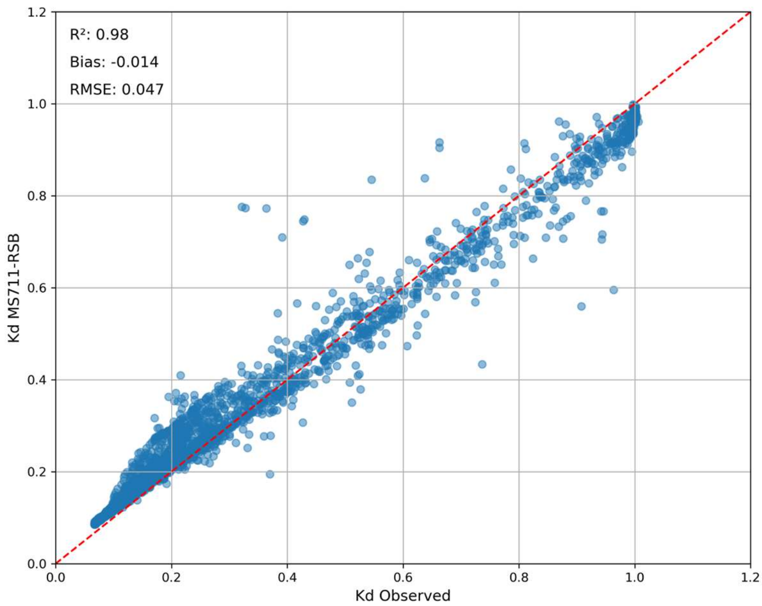

Fig. 4: Validation of diffuse fraction estimates from MS-711-RSB compared to a tracker mounted pyranometer at Madrid (MAD).

Comparisons between the F_{PAR} distributions obtained for each sensor set are presented in Figure 5. For MAD, there are three PAR measurements in addition to the spectroradiometer, while for PSA and CED, there is a single measurement. Table 2 presents the mean values and percentiles for each sensor and region. It can be observed that there is a large variation between the medians of the different datasets. Taking MS711 as a reference, the absolute differences in the median of the PAR fraction between sensors range from [+0.028, -0.035] for MAD, -0.04 for PSA, and -0.059 for CED. It can be noted that the Eko ML-020 sensors present systematically lower values than the MS711 and other Apogee sensors, in many cases being below the expected values for the region (CED). It is also noted that MAD has greater temporal variability (interquartile range) compared to PSA and CED. Preliminary analysis for Cachoeira Paulista (CPA) station in Brazil shows the variability of global horizontal irradiance, PAR irradiance and PAR fraction values for one week campaign in March, 2025. F_{PAR} varies from 0.39 to 0.51, with an average value of 0.45, in accordance with past studies. Variability of F_{PAR} is more pronounced during scattered clouds conditions, evidencing the importance of separate analysis of diffuse and beam PAR irradiances as shown in Figure 6. It confirms that direct or beam irradiance is more spectrally stable, converging to F_{PAR} around 0.43 for MAD. On the other hand, results evidence a larger spread in diffuse spectra, with F_{PAR} ranging from 0.3 to 0.8. It suggests that the type of atmospheric constituent modulating the scattering and absorption physical processes matter for PAR fraction estimates, defining the regional F_{PAR} climatology. This behavior is further detailed in Figure 7 which shows the linear dependence of F_{PAR} on clear-sky index, pointing to smaller fractions (< 0.42) for clear days (Kt > 0.8).

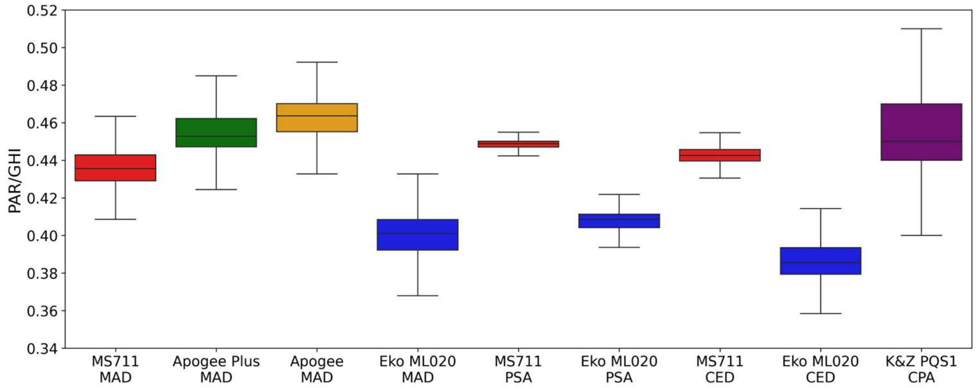

Fig. 5: Boxplots showing preliminary results for sensor and sites intercomparisons in Spain for F_{PAR} variability. Results include one site in Brazil (Cachoeira Paulista)

Table 2. PAR/GHI mean and percentiles for the field campaigns.

Sensor	Mean	Median	P5	P95
	MAD			
MS711	**0.437**	**0.436**	**0.424**	**0.457**
Apogee Plus	0.458	0.453	0.436	0.5
Apogee	0.463	0.464	0.434	0.486
Eko ML020	0.394	0.401	0.377	0.424
	PSA			
MS711	**0.449**	**0.449**	**0.443**	**0.453**
Eko ML020	0.407	0.409	0.387	0.42
	CED			
MS711	**0.443**	**0.443**	**0.435**	**0.449**
Eko ML020	0.387	0.386	0.365	0.408
	CPA			
K&Z PQS1	0.483	0.451	0.395	0.508

Note that the pattern presented between MAD, PSA, and CED for MS711 is consistent with the literature, as the PAR Fraction should be higher in regions with high cloud cover, as clouds absorb more radiation in the infrared spectrum (Ferrera-Cobos *et al.,* 2020). The Eko sensor presents inconsistent values, especially for CED.

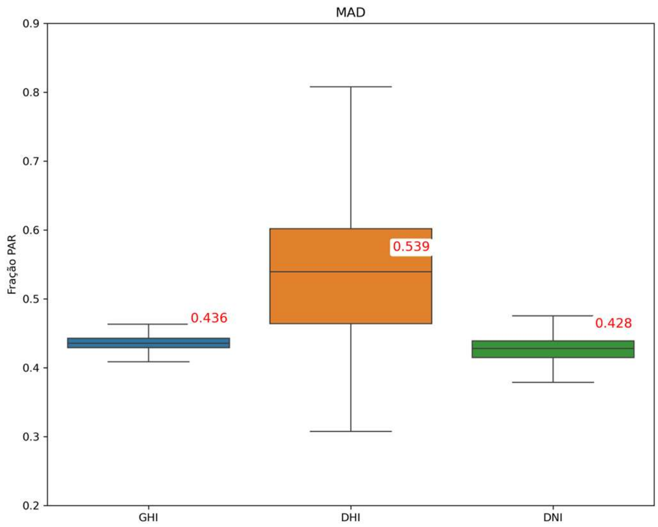

Fig. 6: Validation of diffuse fraction estimates from MS-711-RSB compared to a tracker mounted pyranometer at Madrid (MAD).

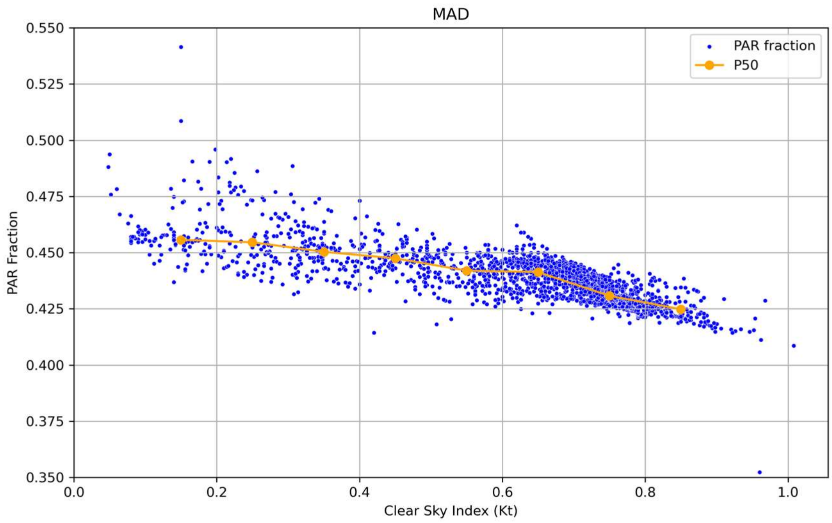

Fig. 7: PAR fraction linear dependence on clear sky index in Madrid (MAD).

3. Conclusions

The results presented above show the first insights for PAR variability at three sites in Spain. The role of clouds in this process is very suggestive for upcoming analysis. Spectroradiometer data processing is ongoing and will be updated with new calibration curves in a future publication. There are other uncertainties to investigate, such as possible bias in the reference GHI as well in the conversion from micromoles to W/m². The preliminary results indicate large dispersion in the PAR Fraction measurements, primarily due to deviations between the PAR sensors. Newer Apogee sensors showed better performance (bias <2%), while older Eko and Apogee sensors showed biases between +0.03 (6%) and -0.06 (-12%) in the F_{PAR} . It is concluded that an assessment of the accuracy and uncertainty of the sensors is necessary before comparing them to models. The next step consists of a review of the accuracy of the MS711 considering new intercomparison data with external standards, as well as an investigation into any possible degradation of the sensors over time. This is a work in progress with all field campaigns planned to finish up to September, 2026. One of the goals is to make public a new set of qualified PAR and PAR fractions measurements with associated uncertainties to validate satellite products in Brazil and Spain.

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