Direct Spectral Irradiance Measurements from Rotating Shadowband EKO Grating Spectroradiometer

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***Abstract* — In this paper, we explore a rotating shadow band (RSB) configuration for the EKO MS-711 spectroradiometer to measure the global, diffuse and direct components of spectral irradiance. An RSB configuration allows lowering the costs associated with the instrumentation and maintenance required to measure the components of spectral irradiance. Since only one spectroradiometer is used for the measurement of the spectral irradiance components, discrepancies associated to sensor calibration can be minimized. This work presents a study to validate the EKO RSB spectroradiometer accuracy in measuring the direct normal irradiance (DNI). A comparison is made between the measurements performed with the RSB spectroradiometer and a collimated spectroradiometer in Mauna Loa Observatory. The results of the comparison show an agreement within 2% to 5% between the DNI estimated by the RSB and collimation configurations for solar zenith angles smaller than 70°. Larger deviations approximated to 10% are found for larger angles of incidence.**

***Index Terms* — instrumentation and measurement, radiometry, solar energy, spectral irradiance.**

I. INTRODUCTION

Spectral irradiance data sets are critical to many environmental science and energy applications [1-3]. To acquire reliable in situ spectral irradiance data, ground-based spectroradiometers are commonly employed [2]. The radiation incident on the Earth's surface is a component summation of direct and diffuse sources. It's commonly described by 3 irradiance components: direct normal irradiance (DNI), diffuse horizontal irradiance (DHI), and the global horizontal irradiance (GHI) which consists of the sum of the direct and diffuse components. The state of the art spectral DNI is measured by continuously tracking the Sun during the day and pointing a collimated spectroradiometer so that only the Sun rays that come straight from the Sun disk are measured by the detector. Opposingly, the spectral DHI is measured by a horizontal static spectroradiometer while constantly blocking the Sun's disk with either a shading ball or shading ring, which also require tracking or manual adjustment. Although very accurate this set up can be costly due to the large number of instruments involved. In a rotating shadow band (RSB) configuration, a narrow band alternates its position to shade and un-shade a detector, allowing a sequential measurement of both in plane global and diffuse irradiance, and the determination of the DNI. An RSB spectroradiometer configuration offers an alternative to tracking, which lowers the costs associated with the instrumentation required, and, since only one detector is used, it also minimizes the discrepancies associated to sensor calibration and the mutual differences regarding individual measurement performance when measuring the spectral irradiance components.

In this study, we explore a rotating shadow band (RSB) configuration for the EKO MS-711 spectroradiometer to measure the global, diffuse, and direct components of spectral irradiance. Firstly, we describe the test site, instrumentation employed, the measurement procedure and campaign. Next, the applied methodology to estimate the DNI with the RSB spectroradiometer is described. The procedure for data analysis is then presented with the results and followed by conclusions.

II. EXPERIMENTAL SITE AND SETUP

The test results presented here were performed during a measurement campaign at the National Oceanic and Atmospheric Administration (NOAA) Mauna Loa Observatory (MLO), on Hawaii island [4]. The facility is located at a remote high-altitude site, above the planetary boundary layer (3397 m above sea level).

During this campaign measurements of the spectral DNI were performed every 1-min by five EKO MS-series spectroradiometers. Four spectroradiometers were set up with collimating tubes to narrow the field of view of the instruments aperture to 5° and assembled on an EKO STR-32G tracker to automatically follow the Sun (Fig 1. left side). Measurement of the spectral GHI and DHI was carried out by one EKO MS-711 spectroradiometer set horizontally and coupled with the recently developed EKO RSB-01S rotating shadow band (Fig. 1 right side). In this setup, the MS-711 detector is centric to the narrow shadow band rotation axis. As the RSB rotates, four measurements are acquired within less than 1-min for four different positions of the shadow band: 1st position the shadow band rests outside of the instrument field of view; 2nd position the shadow band stops at -5º from the Sun disk; 3rd position the RSB covers the solar disk to perform the DHI measurement; 4th position, the shadow band stops +5º after the Sun disk;

The 1st and 3rd position of the RSB are used respectively to measure the spectral GHI and DHI, and, by relating the two measurements to the solar zenith angle (SZA), the spectral DNI can then be estimated,

$$DNI_{\lambda} = \frac{(GHI_{\lambda} - DHI_{\lambda})}{\cos(SZA)} \qquad (1)$$

Fig. 1. Left: MS-700, MS-710, MS-711 and MS-712 mounted on an EKO STR-32G tracker; Right: EKO MS-711 mounted with the RSB-01S rotating shadowband.

The 2nd and 4th positions are then used to estimate the amount of diffuse irradiance lost due to the RSB sky coverage, and a correction is applied to the DHI_λ and replacing it by $DHI_{\lambda corr}$ using eq. 2,

$$DHI_{\lambda_{corr}} = DHI_\lambda + \left(GHI_\lambda - \frac{IRR2_\lambda + IRR4_\lambda}{2} \right) \qquad (2)$$

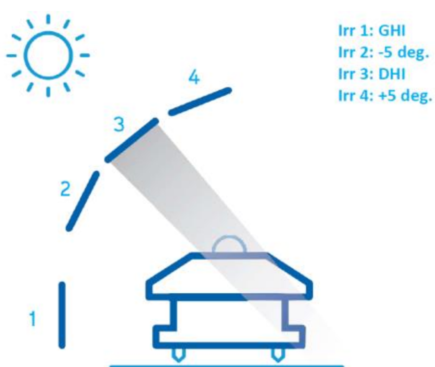

Fig. 2. Rotating shadow band sweeping positions

Prior to this campaign all spectroradiometers were in-house calibrated in the EKO calibration facility in Tokyo, Japan, following the standard spectroradiometer calibration procedure using a National Institute of Standards and Technology (NIST) traceable method [5].

To reduce the amount of uncertainties associated with comparing different instrument types, only the data acquired by the collimated and RSB MS-711 spectroradiometers were considered for the analysis. The EKO MS-711 measures the spectral irradiance in the wavelength range from 300 nm to 1100 nm, with a full width at half maximum (FWHM) < 7 nm. In Table I the instrument main specifications are summarized.

TABLE I
EKO MS-711 MAIN SPECIFICATIONS

	Specification
Wavelength range	300 to 1100 nm
Optical resolution FWHM	< 7 nm
Wavelength accuracy	+/- 0.2 nm
Directional response	< 5 %
Temperature response -10°C to 50°C	< 2 %
Temperature control	25 ± 2 °C
Operating temperature range	-10 to 50 °C
Exposure time	10 to 5000 msec
Field of View	180 °

III. DATA AND COMPARISON

The measurement campaign in MLO took place from 29th of October to 5th of November 2016. For the measurement performance analysis of the RSB configuration, we analyze clear sky days acquired during this measurement campaign. In this paper, data and analysis are shown for the clear sky day of 2nd of November 2016, where the SZA at solar noon reached 34.64°. In Fig. 3, the spectral irradiance measurements for the different positions of the shadow band are shown. In Fig. 4 we plot the measured DNI with the collimated (left) and RSB (right) configurations. To compare the output from both configurations we calculate the difference between the measured DNI and the estimated DNI with the RSB spectroradiometer. The result is then normalized by the measured DNI with the collimated spectroradiometer.

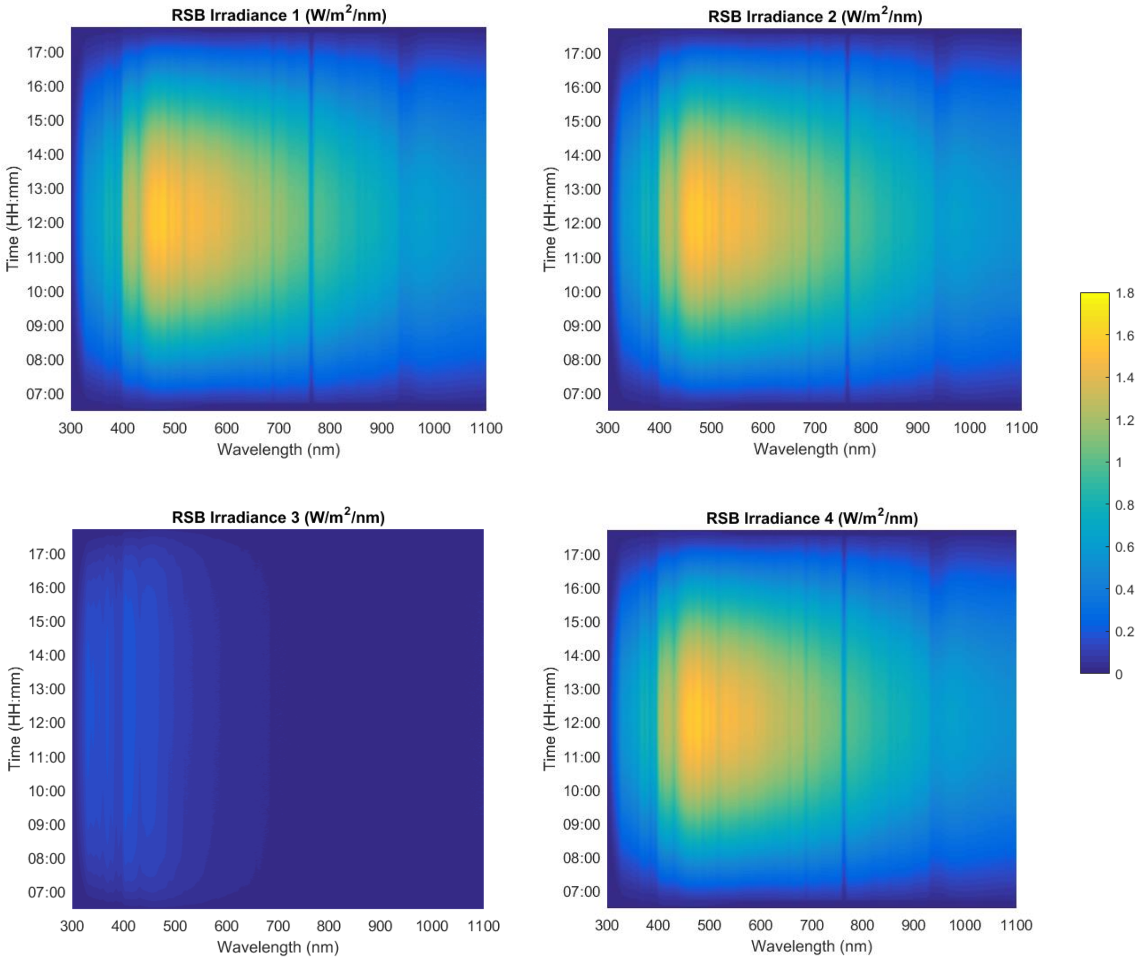

Fig. 3. RSB spectroradiometer measurements at different positions: 1st position GHI, 2nd position band at -5 º, 3rd position DHI, 4th position band at +5º

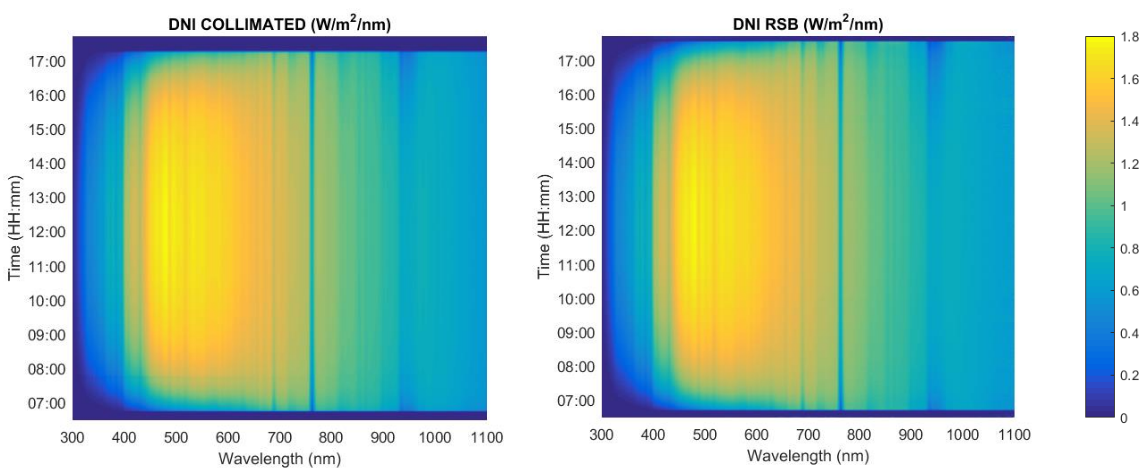

Fig. 4. DNI measurements with collimated spectroradiometer (left) and estimated DNI with RSB spectroradiometer (right)

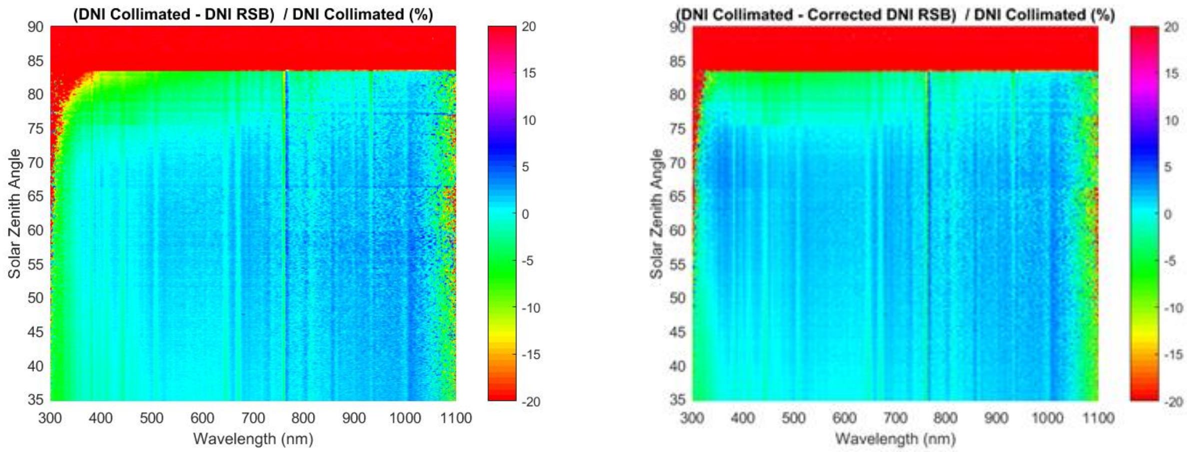

Fig. 5. DNI measurements comparison between rotating shadow band and collimation-tube configurations. DNI comparison for uncorrected DHI (left) and with corrected DHI (right)

The calculations are done by considering the RSB corrected and uncorrected DNI estimates. In Fig. 5, the DNI comparison results are plotted as a function of the SZA for both the uncorrected and corrected DHI measurements.

IV. Conclusions

In this paper, we show preliminary results of the DNI estimations obtained from an MS-711 spectroradiometer with RSB show and compare it with a collimated MS-711 spectroradiometer. The comparison between the spectral DNI from the two configurations reveals a consistency in the methods. Overall the deviations between the RSB and collimated configurations range from 2% to 5% up to 70° SZA's. The discrepancies increase to 10% for SZA's larger than 75° and become greater than 20% above 83°. The band sky coverage correction shows improvements to the estimated DNI in the UV range, especially at narrow angles.

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