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Ground-Based Monitoring of Global Solar Radiation and Ultraviolet Irradiance at NAO Rozhen

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Abstract

In this paper we present first results from continuous ground-based monitoring of global solar radiation and ultraviolet irradiance in the UVA and UVB spectral ranges, based on measurements performed with Kipp & Zonen instrumentation at Rozhen National Astronomical Observatory of the Bulgarian Academy of Sciences. The observations of global solar radiation cover a period of two and a half years, while systematic UV measurements have been conducted for nearly one year. The analysis focuses on the seasonal variability of the radiation fluxes, as well as on evaluation the influence of atmospheric conditions on the recorded values. Comparisons between global radiation and its UVA and UVB components are presented in order to identify correlations and characteristic relationships related to atmospheric transparency and cloud cover. The results reveal a well-defined seasonal variability and highlight the importance of long-term observations for a reliable assessment of the radiation balance. The study contributes to a better understanding of local radiative characteristics and has potential applications in atmospheric physics, environmental studies, and UV exposure assessment.

Keywords: Global Solar Radiation, UV irradiance, Ground-Based Monitoring

1. Introduction

Solar radiation is the primary source of energy for the Earth and plays a fundamental role in determining the surface energy balance and, consequently, in a wide range of atmospheric, climatic, and environmental processes. Variations in the amount of solar radiation reaching the Earth's surface can affect surface temperature, evaporation, the hydrological cycle, snow and ice melt, photosynthetic activity, and the potential for solar energy production [Wild, 2009]. Long-term observations have also demonstrated significant variations in surface solar radiation on decadal timescales, commonly discussed in terms of periods of global dimming and brightening [Wild et al., 2005; Wild, 2009]. These variations emphasize the importance of continuous and reliable measurements of surface solar irradiance.

The amount of solar radiation received at the Earth's surface is determined by both astronomical and atmospheric factors. Solar geometry, and particularly the solar zenith angle, controls the incoming radiation at the top of the atmosphere and its optical path through the atmosphere. At the same time, clouds, aerosols, water vapor, and other atmospheric constituents modify the radiation through absorption and scattering processes. Continuous ground-based observations are therefore important for investigating temporal variations in the surface radiation environment and their relationship with atmospheric conditions.

According to International Organization for Standartization (ISO 9488:2022 - https://www.iso.org/standard/74269.html), global solar irradiance, defined as the total shortwave solar irradiance incident on a horizontal surface, consists of direct solar radiation projected onto that surface and diffuse radiation originating from the sky. Reliable measurements of these radiation components are an important element of surface radiation

monitoring. The need for accurate and long-term observations led to the establishment of the Baseline Surface Radiation Network (BSRN), which provides high-quality ground-based radiation measurements from stations distributed over a wide range of geographical and climatic environments [Ohmura et al., 1998; Driemel et al., 2018]. Such measurements are used in climate research and provide reference observations for the evaluation of radiation products obtained from other observational and modelling approaches.

Ultraviolet (UV) radiation represents a relatively small fraction of the global solar radiation reaching the Earth's surface but is particularly important because of its biological effects. Surface UV irradiance exhibits substantial temporal and spatial variability. Solar zenith angle and stratospheric ozone are among the principal factors determining UV irradiance, while clouds, aerosols, surface reflectivity, and changes in atmospheric composition can further modify the amount of UV radiation reaching the ground [Bais et al., 2015]. These effects are wavelength-dependent and are particularly important at shorter UV wavelengths [Bernhard et al., 2023].

Cloudiness represents one of the major sources of short-term variability in surface UV radiation. Depending on cloud optical properties, cloud fraction, spatial distribution, and the relative position of the Sun and clouds, UV irradiance at the surface may be substantially attenuated and, under particular conditions, may also be locally enhanced [Calbó et al., 2005]. Aerosols constitute another important factor affecting UV transmission through the atmosphere, while changes in stratospheric ozone have a particularly strong effect on the UV-B part of the spectrum [Bais et al., 2015]. Continuous UV measurements can therefore provide valuable information about the temporal variability of the surface radiation environment and its response to changing atmospheric conditions. When observations are extended over months and years, they provide information on seasonal variability and allow the construction of local radiation climatologies. Long and homogeneous observational records are particularly valuable for detecting changes in surface radiation and for distinguishing persistent variations from short-term atmospheric fluctuations [Wild, 2009; Driemel et al., 2018].

Satellite observations provide an important means of estimating solar and UV radiation over large geographical areas and have enabled the development of regional and global radiation datasets. Nevertheless, ground-based observations remain essential because they provide direct measurements at specific locations and can achieve high temporal resolution under continuously changing atmospheric conditions. High-quality surface observations are also required for the validation and assessment of satellite-derived radiation products [Driemel et al., 2018].

The present study describes the ground-based instrumentation used for monitoring global solar radiation and UV irradiance at the National Astronomical Observatory (NAO) Rozhen, located in the Rhodope Mountains in Bulgaria, and presents an analysis of measurements obtained during more than one year of operation. Particular attention is given to the technical characteristics of the installed instruments, their measurement ranges and data acquisition procedures, as well as to the temporal behaviour of the recorded irradiance. The observations are analysed to characterize daily and seasonal variations in global solar and UV radiation and to assess the capabilities of the installed instrumentation for continued radiation monitoring at the observatory.

2. Ground-based station at Rozhen NAO

Following the commissioning of the new 1.5-m robotic telescope at NAO Rozhen in 2023, a new ground-based meteorological station was established to support astronomical observations. A dedicated mast was installed at the observatory site (41°41′48″ N, 24°44′18″ E; altitude 1730 m), on which most of the meteorological instruments are mounted. One of the

primary purposes of the new instrumentation is to continuously monitor the meteorological conditions during astronomical observations, thereby helping to ensure the safety of the equipment and the quality of the acquired images. Also the long-term collection of meteorological data is of particular scientific importance, as it will provide a valuable statistical dataset for a detailed characterization of the local climate and the specific meteorological conditions at the observatory site. In addition to the standard meteorological instrumentation, sensors for global solar radiation and ultraviolet (UV) radiation have been installed on the mast. Their purpose extends beyond the routine collection of daytime solar radiation and sunshine data. Measurements of solar radiation may be directly or indirectly related to processes associated with solar–terrestrial interactions and can therefore complement other studies conducted at the observatory in this field. These include optical observations of solar activity in Hα, Ca II, and visible light, neutron monitoring, observations of geomagnetic disturbances, and muon monitoring, for which a dedicated detector is planned.

2.1. Weather Monitoring

For continuous monitoring of the meteorological conditions, an automated Davis Vantage Pro2 weather station is used. The system measures ambient air temperature, relative humidity, dew-point temperature, wind speed and direction, and atmospheric pressure. The station is also equipped with an additional module for measuring global solar radiation and determining the UV index. However, a comparison of these measurements with those obtained from the dedicated solar-radiation sensors has not yet been performed and will be addressed in future work. Although the sensors integrated into the Davis station have comparatively lower accuracy, greater response times, and lower long-term stability than dedicated scientific-grade instruments, the system provides a valuable continuous meteorological record due to its autonomous operation. The station is powered by a solar panel and battery system, allowing it to operate for at least six months without an external power supply. In the event of an internet connection failure, the acquired data are stored locally and can be transferred once the connection is restored. This feature is particularly important during the severe winter months, when the observatory may occasionally experience prolonged power outages, potentially lasting long enough to exhaust the available UPS systems.

For more precise measurements of air temperature and relative and absolute humidity, an OTT TRH Temperature and Humidity Sensor is used. The technical specifications of the sensor are available from the manufacturer's documentation. In addition, we have a Cloud Watcher to measure cloudiness in the vicinity of the zenith and an all-sky camera, the data from which is to be implemented in future work.

2.2. Solar Radiation Monitoring

Solar radiation is monitored using instrumentation manufactured by Kipp & Zonen, a leading company specializing in precision solar-radiation and atmospheric measurements. Their Class A pyranometers are widely used as reference instruments and are designed to provide high stability over long-term operation. At NAO Rozhen, SMP12 and SMP22 pyranometers are used for monitoring global solar radiation. The high-quality construction of the instrument domes, together with their integrated heating systems, minimizes the effects of condensation and icing and thus helps maintain the accuracy and reliability of the measurements under the harsh environmental conditions at the observatory site.

The ultraviolet radiation reaching the Earth's surface is conventionally divided into three spectral ranges: UVA (315-400nm), UVB(280-315nm), and UVC(100-280nm) [Mondal & Ghosh, 2019]. UVC represents the shortest-wavelength component of UV radiation, but only a very small fraction reaches the Earth's surface, making its detection at ground level particularly challenging. In contrast, UVA and UVB radiation can be measured reliably using ground-based

sensors. For this purpose, Kipp & Zonen SUV-A and SUV-B UV radiometers are used at NAO Rozhen. The main technical specifications of the instruments employed in the monitoring system are summarized in Table 1.

Table 1. *Technical specifications of the Kipp & Zonen radiometers at Rozhen Observatory.*

Sensor	Global Solar Radiation	UV-A	UV-B
Spectral Range	280 to 3000 nm	315 to 400nm	280 to 315 nm
Maximum Irradiance	2000 W/m²	90 W/m²	9 W/m²
Operating Temperature	-40 to 70 ⁰C	-40 to 70 ⁰C	-40 to 70 ⁰C
Operating Humidity	0 to 100%	0 to 100%	0 to 100%
Field of View	180⁰	180⁰	180⁰
Response Time	0.5 s	0.2 s	0.2s
Non-Linearity	< ±0.2%	± 1%	± 1%
Temperature Response	< ±1%	± 1%	± 1%

3. Processing and Analysis of Solar Radiation Data

The Kipp & Zonen solar-radiation sensors allow measurements to be acquired at one-minute intervals, resulting in a continuous time series of measurements. To facilitate data processing and avoid handling excessively large tables of numerical values, we developed a dedicated script that automatically separates the measurements into individual daily files. Thus, each day is represented by a separate file containing up to 1440 one-minute measurements. As a subsequent processing step, the script removes measurements with values below 1% of the maximum irradiance that can be detected by the respective sensor. These low values generally correspond to noise measurements obtained during the nighttime period. As a result, the raw data containing a large number of measurements are converted into daily files containing only the detected solar irradiance from sunrise to sunset. This representation also allows the duration of daylight to be determined directly from the data. The data are stored in a three-column format containing the time, date, and measured irradiance, (i.e. HHMMSS DDMMYY signal). This simple format allows the files to be readily processed using other text-based data-analysis platforms and software packages, including Python, GNUplot, MATLAB, and others.

At present, an online platform has been developed for visualization of measurements acquired during the previous several days, as well as for downloading the corresponding raw data files. The platform is available at: https://meter.ac/gs/meteo/M26/history.html. Although the web-based visualization is convenient for a quick inspection of the measurements, it is not particularly suitable for more detailed data analysis. Therefore, we developed a dedicated application using the Visual Basic platform for visualization and analysis of the daily data files. In addition to data visualization, the application displays the maximum solar irradiance measured during each day and provides the possibility of fitting a Gaussian function to the daily irradiance profile. The coefficient of determination, (R^2), is calculated for each fit as a quantitative measure of the quality of the fit (Figure 1 - top). The software can process multiple daily data files either manually, by selecting individual dates of interest, or automatically. In the automated mode, a log file is generated containing, for each analyzed day, the date, duration of daylight, time and value of the maximum measured irradiance, and the corresponding (R^2) value of the Gaussian fit. The (R^2) parameter is used as the primary indicator of the quality of the measurements for a given day and provides an initial assessment of whether the solar-irradiance profile was affected by passing clouds. However, a low (R^2) value does not necessarily imply that the entire dataset for a given day is unsuitable for analysis. For example, a temporary interruption of the internet connection or a short period of cloud coverage may affect only a small fraction of the measurements while leaving the majority of the daily dataset

unaffected. In such cases, a scientifically meaningful analysis may still be possible despite a relatively low overall (R^2) value. To account for this limitation, the application provides an automatic classification of the analyzed days according to their (R^2) values into five categories: very bad, bad, good, very good, and excellent. The data assigned to the last three categories, which are intended for subsequent analysis, should nevertheless be visually inspected individually in order to confirm their reliability and identify possible short-duration disturbances that may not be adequately characterized by the (R^2) parameter alone.

The software has already been extended to support the visualization of measurements in different spectral ranges, including global solar irradiance, UV-A, and UV-B radiation, as well as the integration of data from the Cloud Watcher and OTT TRH sensors for cloud conditions, humidity, and temperature (Figure 1 - bottom). Further development is currently focused on optimizing the software and implementing direct comparisons between the different spectral ranges, as well as investigating their relationships with the local meteorological conditions.

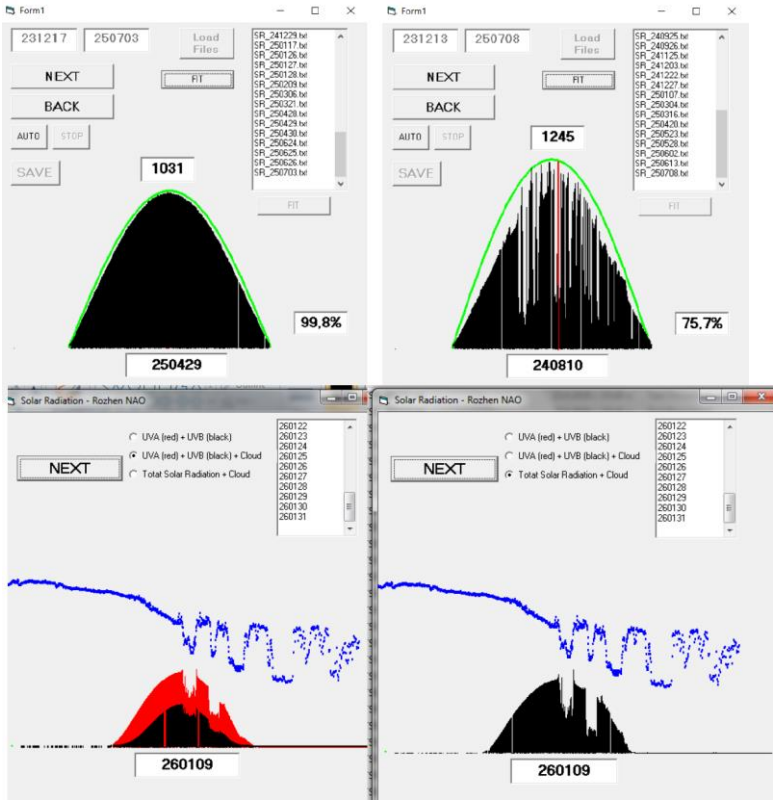

Figure 1. *Screenshots from our developed software for visualization of daily files with solar irradiance measurements. Top: global solar radiation with Gaussian fit, maximum solar irradiance and coefficient of determination (R^2). Bottom: comparisons between different spectral ranges of solar irradiance and cloud cover.*

4. First Results from Solar Radiation Monitoring

Measurements of global solar irradiance at NAO Rozhen started at the end of 2023, while the UV sensors have been operational since mid-2025. In this section, we present the first results obtained from the monitoring system to date.

4.1. Global Solar Radiation

From mid-December 2023 to May 2026, the global solar irradiance dataset contains measurements from 749 days. This number is lower than the total number of calendar days in the corresponding period because, during the initial stage of operation, additional time was

required to fully establish and optimize the radiation-monitoring system. Some data were also lost due to internet connectivity failures, server-related problems, power interruptions, and other technical issues. These problems have subsequently been resolved, and the monitoring system is now capable of continuous operation without significant data loss. Based on the measurements obtained so far, approximately 25% of the analyzed days were characterized by predominantly clear skies or only short-duration cloud passages that did not significantly affect the determination of the daily maximum solar irradiance (R^2 > 90%). Days characterized by significant cloud coverage (R^2 < 50%) account for approximately 20% of the dataset, while days with persistent and dense cloud coverage (R^2 < 25%) represent approximately 10%. The distribution of the number of days as a function of the R^2 value obtained from the Gaussian fit to the global solar irradiance data is presented in Figure 2.

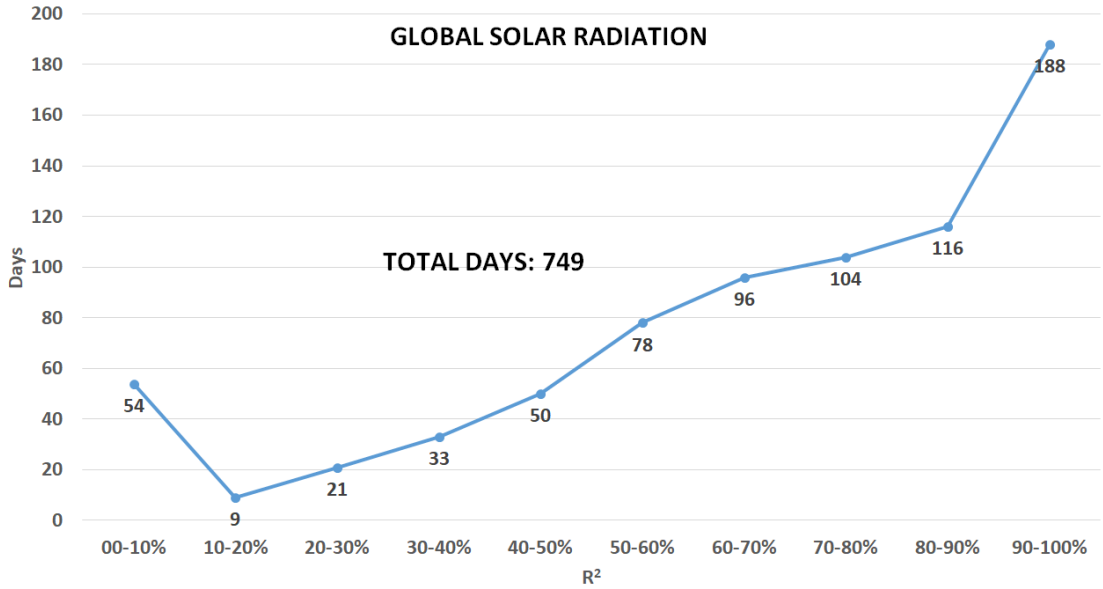

Figure 2. *The distribution of the number of days as a function of the R^2 value obtained from the Gaussian fit to the global solar irradiance data.*

For days with sufficiently high-quality measurements, for which the daily maximum solar irradiance can be reliably determined, an annual variation curve can be constructed for the specific location of NAO Rozhen (Figure 3). The data collected so far clearly reveal the seasonal variation, with the two summer maxima in 2024 and 2025 and the corresponding winter minima being readily distinguishable. At the winter minimum in 2025, a decrease in the measured global solar irradiance of approximately 5% compared with the corresponding minimum in 2024 can be observed. However, the current dataset is not yet sufficiently long to support robust statistical conclusions regarding such year-to-year variations. A more comprehensive analysis will become possible as additional measurements are accumulated over the coming years. In particular, future studies will investigate possible relationships between the observed solar irradiance and solar activity and the solar cycle, as well as possible correlations with local meteorological conditions. An illustrative example of full-day measurements of global solar irradiance during different months of the year is presented in Figure 4.

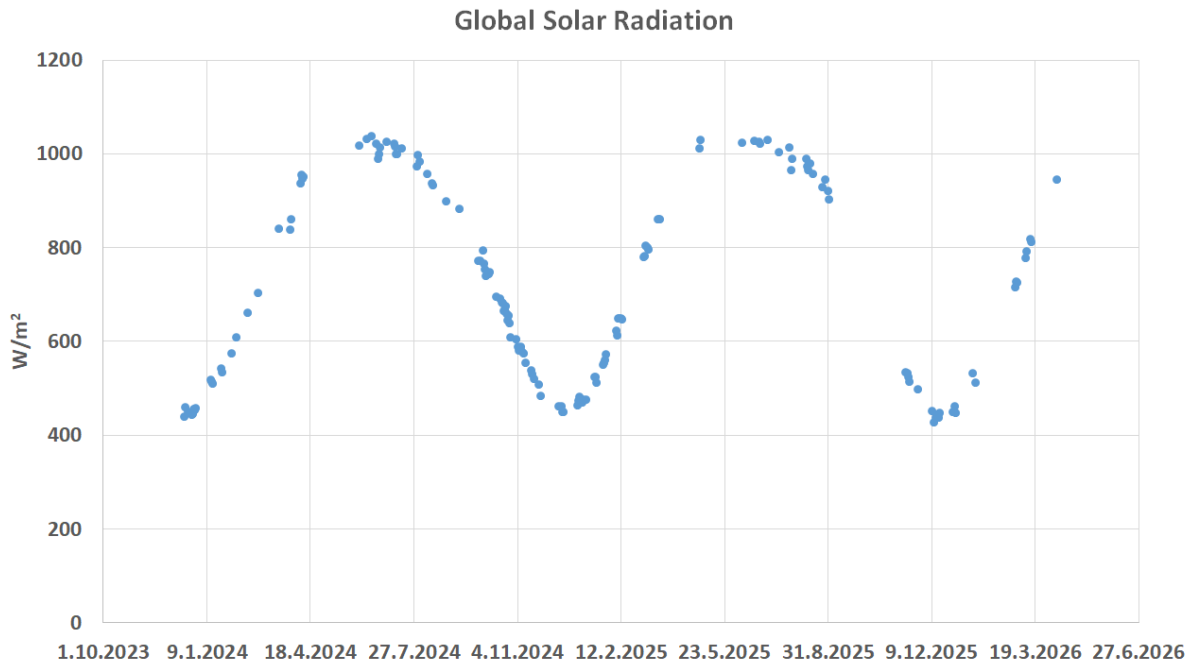

Figure 3. *An annual variation of daily maximum global solar irradiance from NAO Rozhen site from December 2023 to May 2026.*

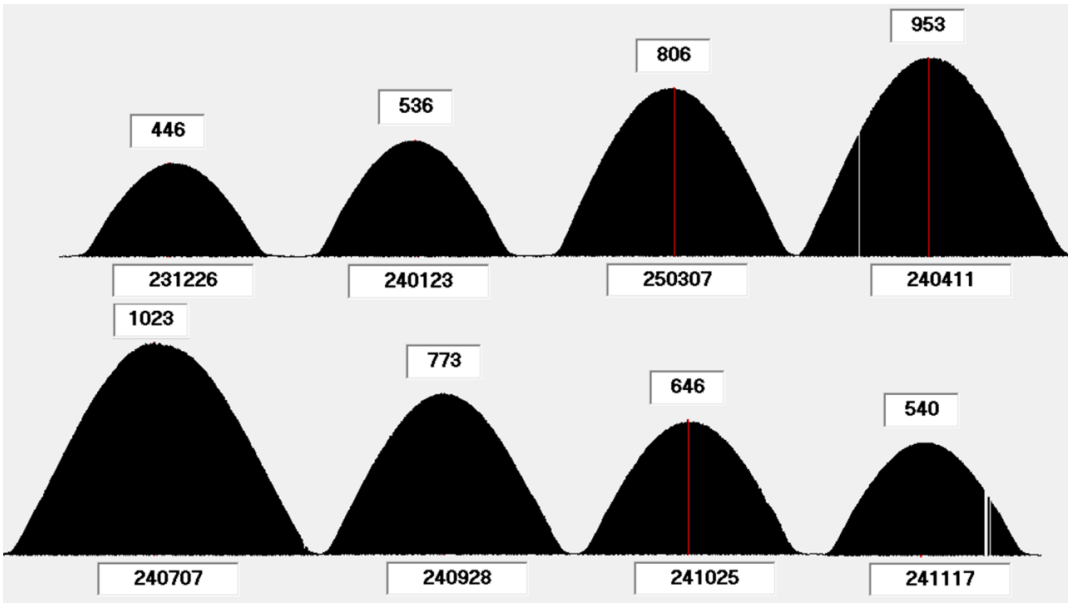

Figure 4. *An illustrative example of full-day measurements of global solar irradiance during different months of the year.*

Since the measured solar irradiance may be affected by atmospheric scattering and absorption associated with water vapor, we investigated whether the maximum daily irradiance shows a measurable dependence on relative humidity [e.g. Swartman & Ogunlade, 1967 and Kirmani et al., 2015]. For this purpose, we selected a period comprising a sequence of relatively close consecutive days, from 18 October to 11 November 2024, for which a sufficient number of measurements was available and during which relative humidity covered a comparatively broad range of values. Over this period, we assumed a linear daily decrease in the solar irradiance. After applying the fitted model, the individual deviations (residuals) were calculated for each measurement point. The subsequent analysis was aimed at determining whether these

residuals were consistent with random variations or whether they exhibited a systematic dependence on an external parameter as relative humidity. The correlation between the regression residuals and the varying relative humidity was examined, allowing the influence of humidity on the measured solar irradiance to be quantitatively assessed. The residual plot shows a clear correlation with the relative humidity level, indicating that atmospheric humidity acts as a systematic factor affecting the measured global solar irradiance and producing deviations from the idealized linear model (Figure 5.). Within the investigated range, the relationship can be approximated by a linear dependence, described by the following equation:

$$-0.0951\text{Hum} + 3.3831 = \alpha, \quad (1)$$

However, this result is currently limited to the relative humidity range of approximately 20–60%, and extrapolation beyond this range, particularly toward substantially higher humidity values, may not be justified. The resulting correction to the measured irradiance is of the order of ±2%. A comparison between the measured solar irradiance before and after applying the humidity correction is presented in Figure 6. It should be emphasized that the humidity correction presented here is preliminary and is based on a relatively limited observational interval. A longer time series, covering a broader range of atmospheric conditions and seasons, will be required to establish the robustness of this relationship and to determine whether the observed dependence can be reliably incorporated into the standard data-reduction procedure.

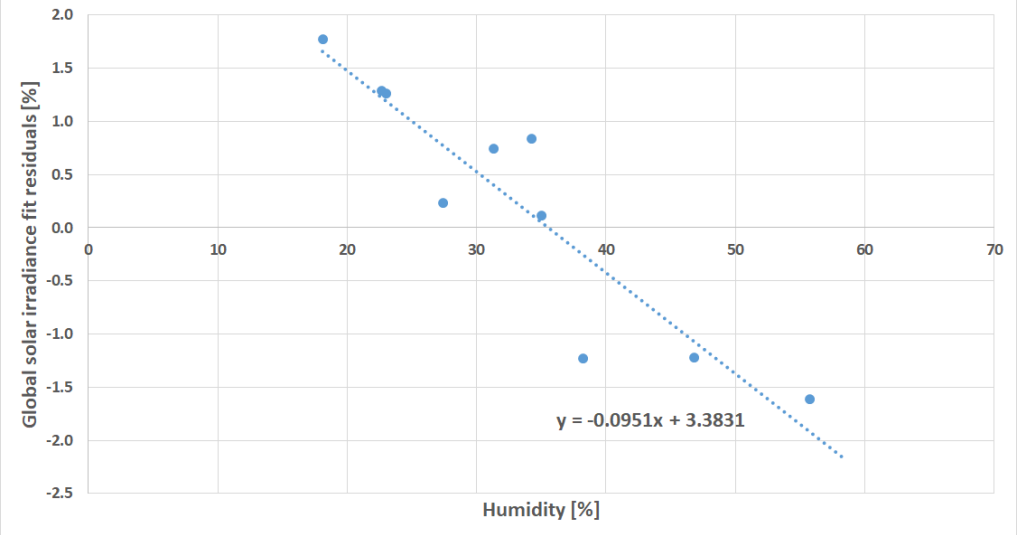

Figure 5. *The correlation between the measured global solar irradiance regression residuals and the varying relative humidity. The residual plot shows a clear correlation with the relative humidity level.*

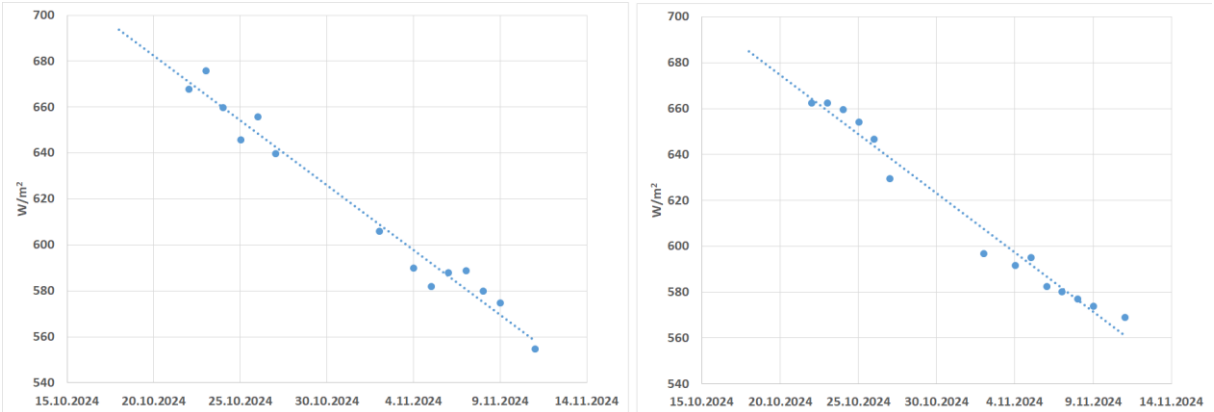

Figure 6. *A comparison between the measured solar irradiance before (left) and after (right) applying the humidity correction coefficient α.*

4.2. UV Irradiance

The measurements obtained from the UV sensors currently cover approximately one year, with continuous operation having started in mid-July 2025. The maximum daily values of UVA and UVB irradiance are presented in Figure 7, where a pronounced seasonal variation, including clear winter minima, can be observed. Figure 8 presents a comparison between the UV irradiance and global solar irradiance, with both quantities normalized to their respective minimum values. The preliminary data collected so far indicate differences in the number of apparently clear days identified from the UV measurements compared with those identified from the global solar irradiance data. One possible explanation for this behavior is the wavelength-dependent response of atmospheric scattering and absorption, as well as the influence of clouds and other atmospheric constituents on different parts of the electromagnetic spectrum. Consequently, atmospheric conditions that produce a relatively weak effect on the global solar irradiance may have a more pronounced effect in the UV range, or vice versa. Differences between the daily profiles of UVA and UVB irradiance are also observed on some days (Figure 9). These differences may provide additional information about the wavelength-dependent effects of atmospheric absorption and scattering and, potentially, about changes in atmospheric conditions during the day. The results presented here are preliminary, as the available UV dataset covers only approximately one year. A significantly longer observational baseline will be required to establish the statistical significance of the observed differences, investigate their seasonal dependence, and determine the relative contributions of cloud cover, atmospheric humidity, aerosol loading, solar elevation, and other atmospheric parameters. The simultaneous measurements of UVA, UVB, and global solar irradiance, combined with the meteorological data collected at NAO Rozhen, provide a basis for a more detailed investigation of these effects as the observational dataset continues to grow.

5. Conclusions

A comprehensive ground-based monitoring system for meteorological conditions and solar radiation has been established at the National Astronomical Observatory (NAO) Rozhen in support of astronomical observations and long-term environmental studies. The system combines automated meteorological measurements with dedicated observations of global solar irradiance and ultraviolet radiation, providing a continuous dataset for the characterization of atmospheric conditions at the observatory site.

Global solar irradiance measurements have been available since the end of 2023, while the UVA and UVB measurements commenced in July 2025. The analysis of the available global solar irradiance data already reveals a clear seasonal variation, with pronounced summer maxima and winter minima. The analysis of the available measurements also indicates that atmospheric humidity may introduce a systematic effect into the measured global solar irradiance. Within the investigated relative humidity range of 20–60%, the observed dependence can be approximated by a linear relation, with a corresponding correction of approximately ±2%. The first year-long series of UVA and UVB measurements shows pronounced seasonal variability, including distinct winter minima. Differences between the temporal profiles of UVA and UVB radiation are also observed on individual days. These preliminary results suggest that the simultaneous monitoring of different spectral components of solar radiation may provide additional information about wavelength-dependent atmospheric effects, including the influence of clouds, water vapour, aerosols, and other atmospheric constituents.

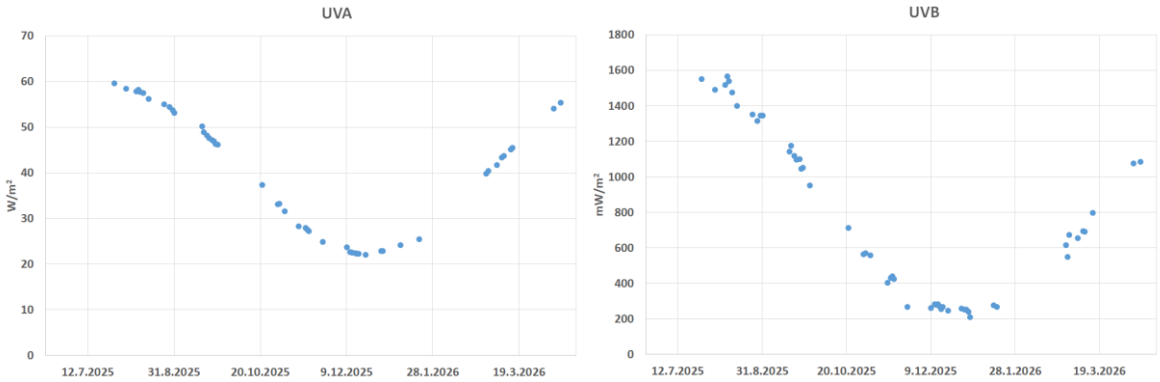

Figure 7. *The maximum daily measured values of UVA (left) and UVB (right) irradiance.*

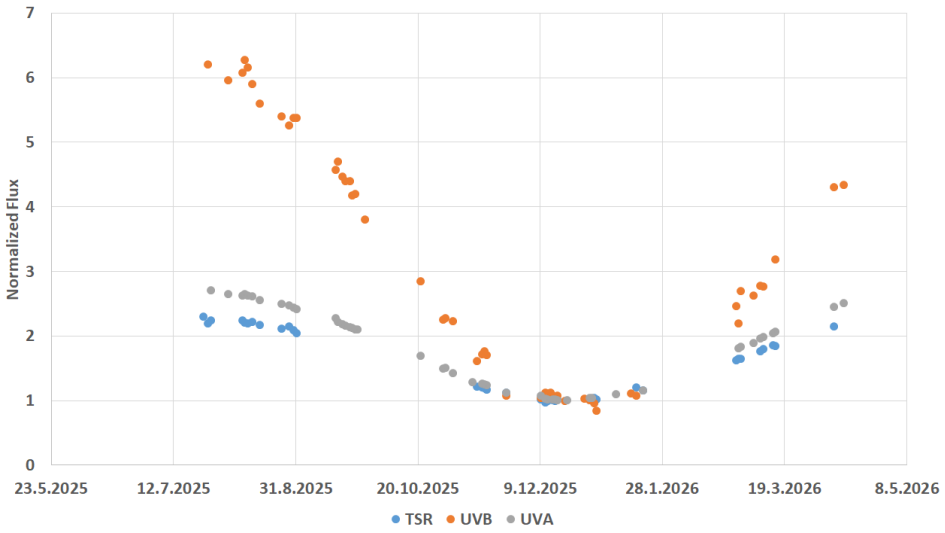

Figure 8. *A comparison between the UV irradiance and global solar irradiance, with both quantities normalized to their respective minimum values.*

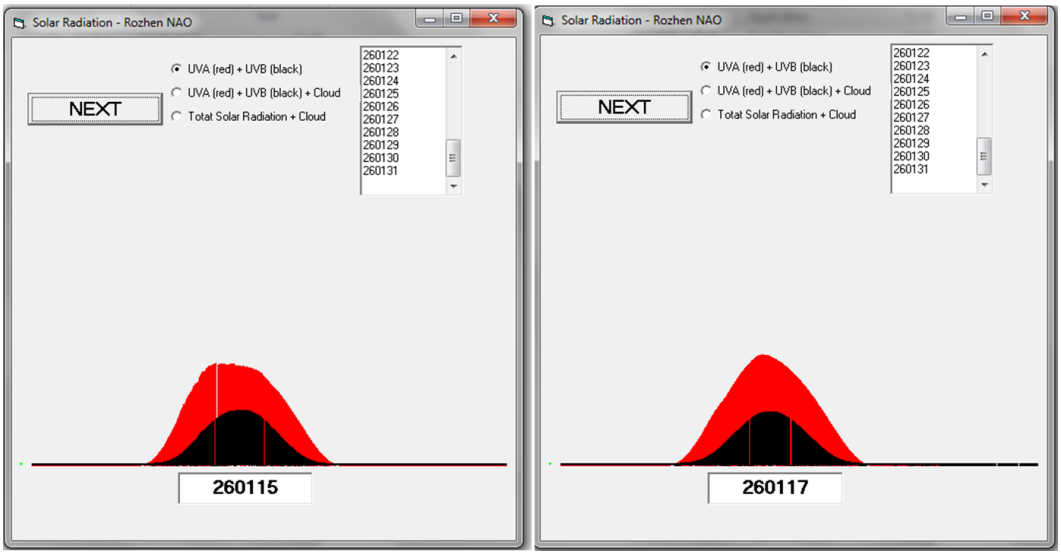

Figure 9. *Differences between the daily profiles of UVA and UVB irradiance observed on 15th and 17th January 2026.*

The monitoring system and the datasets accumulated so far provide a foundation for several directions of future research. With the continuation of the observations, it will be possible to

investigate in greater detail the seasonal and interannual variability of solar irradiance, its relationship with solar activity and the solar cycle, and its dependence on local meteorological conditions. The simultaneous measurements in different spectral ranges will also allow a more detailed investigation of the atmospheric transmission of solar radiation and the relative effects of cloud cover, humidity, aerosols, and other atmospheric parameters. The combination of long-term meteorological observations, global solar irradiance measurements, and UVA and UVB monitoring represents a valuable extension of the observational capabilities of NAO Rozhen. This ground-based system provides a continuously growing scientific dataset that can contribute to the study of local atmospheric conditions and solar–terrestrial interactions. The continued operation and further development of the monitoring network will therefore provide both practical benefits for astronomical observations and new opportunities for interdisciplinary research in atmospheric and solar–terrestrial physics.

Acknowledgements

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