INTERNATIONAL

Designation: G222 – 21

Standard Practice for
Estimation of UV Irradiance Received by Field-Exposed Products as a Function of Location[1]

This standard is issued under the fixed designation G222; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice describes methods to estimate the total solar ultraviolet irradiance on a horizontal surface as a function of Air Mass and geographic location.

1.2 This practice provides a mathematical model for calculating Global Horizontal Ultraviolet irradiance (GHUV) from Global Horizontal Irradiance (GHI) data for a specific location.

1.3 *Units*—The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.5 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D7869 Practice for Xenon Arc Exposure Test with Enhanced Light and Water Exposure for Transportation Coatings

E772 Terminology of Solar Energy Conversion

G113 Terminology Relating to Natural and Artificial Weathering Tests of Nonmetallic Materials

G173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

G177 Tables for Reference Solar Ultraviolet Spectral Distributions: Hemispherical on 37° Tilted Surface

G183 Practice for Field Use of Pyranometers, Pyrheliometers and UV Radiometers

2.2 *ISO Standards:*[3]

ISO/TR 17801 Standard Table for Reference Global Solar Spectral Irradiance at Sea Level — Horizontal, Relative Air Mass 1

ISO 9060:2018 Solar Energy — Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation

3. Terminology

3.1 *Definitions:*

3.1.1 Definitions applicable to this practice can be found in Terminologies E772 and G113.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *Diffuse Horizontal Irradiance (DHI), W·m^{-2}, n*—the total solar irradiance received on a horizontal plane that has been scattered or diffused by the atmosphere.

3.2.2 *Direct Normal Irradiance (DNI), W·m^{-2}, n*—the total irradiance received on a plane normal to the sun within a 5° concentric field of view around the sun.

3.2.3 *Global Horizontal Irradiance (GHI), W·m^{-2}, n*—the total solar irradiance received on a horizontal plane measured directly using a pyranometer with a hemispherical view, or calculated as the sum of Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI) each measured or modeled independently:

$GHI = DHI + DNI * \cos(\theta_z)$ where θ_z is the solar zenith angle.

3.2.3.1 *Discussion*—The wavelength range reported for field measurements of GHI varies with the pyranometer design and application. Commercial pyranometers generally measure over the 300–3000 nm range, from near the solar cut-on and cut-off (see ISO 9060). This is sufficient for weathering and durability testing applications because 95 % of the solar irradiance on a surface is from wavelengths < 1800 nm. Standard reference spectra for different applications vary in the

[1] This practice is under the jurisdiction of ASTM Committee G03 on Weathering and Durability and is the direct responsibility of Subcommittee G03.09 on Radiometry.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from International Organization for Standardization (ISO), ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, https://www.iso.org.

wavelength range they report. For example, ISO 17801 reports values from 285–2400 nm, whereas ASTM G173, which was developed primarily for photovoltaic energy applications, reports from 280–4000 nm.

3.2.4 *Global Horizontal UV irradiance (GHUV), W·m^{-2}, n*—the ultraviolet solar irradiance received on a horizontal plane for wavelengths shorter than those for visible irradiance and longer than the solar cut-on where the upper limit varies with the ultraviolet radiometer design. GHUV shall be reported using the following format designating the wavelength range over which it is valid: GHUV(X–Y) where X is the minimum wavelength and Y is the maximum.

3.2.4.1 *Discussion*—GHUV values for the range 295–385 nm, denoted as GHUV(295–385), have historically been measured and reported by solar radiation monitoring stations, especially from outdoor exposure testing service suppliers. This range traces back to the early use of spectroradiometers with a spectral range of 295–385 nm. Another commonly reported value is GHUV(280–400) that combines the UVA and UVB ranges of solar ultraviolet irradiance (see Terminology G113). Some radiometers measure the total UVA and UVB irradiance directly while others measure them independently; GHUV(280–400) is then calculated as the sum of the values obtained.

3.2.5 *Solar cut-on, n*—the wavelength at which the solar irradiance on a plane is greater than 0.001 W/m^2/nm. For practical weathering and durability exposure testing purposes, the lowest wavelength at which this value can occur is 295 nm under ideal conditions (for example, ASTM G177); see Appendix X3 (**1**).[4]

4. Summary of Practice

4.1 The mathematical model described in this practice provides a simple way to estimate the representative contribution of UV to the total solar irradiance on a horizontal surface through the ratio GHUV/GHI.

4.2 Data for GHI may be obtained from measurements or modeled datasets (**2**).

4.3 The method requires GHI input of good quality. Practice G183 provides details about standard practice of field measurements of solar radiometric data. If GHI is not reliably measured on site, low-uncertainty modeled estimates should be used instead.

4.4 The Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) atmospheric transmission code was used to generate ratios of ultraviolet to total solar radiation, as a function of air mass for multiple locations with site specific surface albedo, and atmospheric constituents such as aerosols, water vapor or ozone. The mathematical model described in this practice generalizes these ratios to any geographical location with an estimation of accuracy.

5. Significance and Use

5.1 Products exposed outdoors degrade due to primarily three stress factors: sunlight, temperature and moisture. The rate of property change is a function of time and stressors' intensity.

5.2 Whereas the UV irradiance calculated in this practice is independent of material, it is especially relevant to polymeric materials exposed outdoors as the combined action of UV radiation and oxygen is often the dominant factor leading to their degradation. Therefore, estimating UV irradiance is an important parameter to assess the service life of products.

5.3 UV radiant dosage is often more important to determine in the correlation with the amount of degradation than total solar radiant dosage or duration of time. The comparison of UV radiant dosage from one location to another may be used to normalize degradation results.

5.4 Measured UV irradiance data are scarce compared to total solar irradiance data. Many locations that monitor solar resource data only collect data for total solar radiation. This practice allows the user to estimate the amount of UV irradiance from the amount of total solar irradiance for any site.

6. Estimating the Contribution of UV Light to the Solar Irradiance on a Horizontal Surface

6.1 Under clear-sky conditions, GHUV and GHI can be simulated using the SMARTS spectral radiation model, as described by Gueymard (**3-5**). This practice is based on version 2.9.8 of SMARTS (**5**).

6.2 Eq 1, as described by Habte et al. (**6**), was created by fitting GHUV and GHI data as a function of air mass for multiple SMARTS simulations and for different locations, surface albedo, and atmospheric constituents such as aerosols, water vapor or ozone. The SMARTS outputs can be directly compared to what would be obtained under the conditions pertaining to the ASTM G177 standard spectrum, since the latter was developed with SMARTS.

$$\frac{GHUV}{GHI} = \sum_{i=0}^{4} m_i AM^i \tag{1}$$

where:

$GHUV$ = global horizontal UV irradiance, W/m^2
GHI = global horizontal irradiance, W/m^2
m_i = location-specific numerical coefficients
AM = air mass coefficient

Eq 1 can be directly used with AM values obtained from climate data files with hourly, or more frequent, data. Most data sources will include a measure of the solar zenith angle (θ_z); see 3.2.3. The solar zenith angle should be obtained from a solar geometry calculator. The air mass may also be calculated from the value of the solar zenith angle using equation for solar zenith angles below 80° (**7**).

$$AM = \frac{1}{\left[\cos\ (\theta_z) + 0.48353 \times \theta_z^{0.09585} / (96.741\ -\ \theta_z\ )^{1.754}\right]} \tag{2}$$

where θ_z is the solar zenith angle, with $\theta_z < 80$.

6.3 The m_i coefficients used in Eq 1 are location specific. A set of m_i coefficients for 15 locations are proposed by Habte et

[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.

al. (6). If location-specific m_i coefficients are not available, mean m_i values and the upper and lower bounds of the 95 % confidence interval are listed in Table 1 for the GHUV(280–400)/GHI ratio and the GHUV(295–385)/GHI ratio. They are based on descriptive statistics of m_i coefficients calculated to provide the best fit for 15 locations across representative latitudes and atmospheric conditions used by Habte et al. (6).

6.4 The amount of UV radiation at the earth's surface varies with atmospheric conditions, such as air mass (AM), ozone concentration, aerosol optical depth (AOD), amount of precipitable water (PW), atmospheric pressure, surface albedo, or cloud fraction. The mean m_i coefficients estimate the mean GHUV/GHI ratios. The lower and upper bounds describe the expected range of the GHUV/GHI ratios due to site-specific atmospheric conditions and are based on the lower and higher ratios measured for the 15 aforementioned locations (see Fig. 1).

7. Estimating the UV Irradiance Incident on a Horizontal Surface as a Function of Location

7.1 The modeled GHUV/GHI ratios obtained from Eq 1 shall then be multiplied by available, location-specific GHI data to obtain the UV irradiance incident on a horizontal surface for a given location.

7.2 A listing of publicly available Solar Resource Data sets with GHI values for a wide range of global locations is available in Table 5-1 of the *Best Practices Handbook for the Collection and Use of Solar Resource Data for Solar Energy Applications: Second Edition* (2). Most of these Solar Resource Data include both the solar zenith angle and GHI. The solar zenith angle and GHI are the minimum data required to calculate the UV irradiance incident on a horizontal surface, using the mean m_i coefficients listed in Table 1 for GHUV (280–400) and GHUV (295–385).

8. Converting Irradiance to Radiant Exposure

8.1 When the average irradiance is known over the exposure period, the radiant exposure (often referred to as the radiant dosage) shall be determined following the physical relationship between power and energy:

$$\text{Average Irradiance (W/m}^2\text{)} \cdot \text{Expsoure Time (Seconds)} = \text{Radiant Exposure (J/m}^2\text{)} \quad (3)$$

8.2 Given that exposure times are typically long in duration (often expressed in hours, days or months), and radiant exposure is commonly reported in megajoules per square meter (MJ/m^2), conversions from seconds to hours and joules to megajoules may be applied. Combining these conversions results in the following formula (note the difference in the units used):

$$\text{Average Irradiance (Watts/m}^2\text{)} \cdot 0.0036 \cdot \text{Time (Hours)} = \text{Radiant Exposure (MJ/m}^2\text{)} \quad (4)$$

8.3 Where 0.0036 is a factor combining the conversion of seconds to hours and joules to megajoules. Other factors may be used if the exposure period is desired to be expressed in days, months, etc. or if the radiant exposure is expressed in other units, such as kJ/m^2.

8.4 When exposure duration is to be calculated given an average irradiance and radiant exposure, the above formula can be changed using common algebraic functions, as follows:

$$\text{Time (hours)} = \frac{\text{Radiant Exposure (MJ/m}^2\text{)}}{\text{Average Irradiance (W/m}^2\text{)} \cdot 0.0036} \quad (5)$$

NOTE 1—This is commonly done to equate the radiant dosage in accelerated aging and in natural exposures. Users are strongly cautioned that matching the radiant exposure in accelerated and natural exposures does not imply that the exposed materials will experience the same degree of property change, as other factors also influence the degradation of materials, such as temperature, moisture, spectral power distribution of the UV source, potential secondary weathering effects, and synergistic relationships between all of these weathering factors.

NOTE 2—It is important to remember that the wavelength (or wavelength range) for both irradiance and radiant exposure shall be the same. In other words, if the GHUV range of 295–385 nm is used, then the radiant exposure should also be expressed in that wavelength range.

NOTE 3—As mentioned in Note 1, it is sometimes of interest to compare the outdoor radiant exposure to an artificial weathering radiant exposure. To calculate the equivalent radiant exposure in artificial weathering, users shall input the number of light hours, when the artificial light is on, not necessarily the total test time, if the test includes periods of exposure in the dark.

NOTE 4—Because different UV wavelengths can cause both qualitative and quantitative differences in degradation, the calculation is valid only for artificial UV sources that closely match the UV spectrum of natural sunlight, such as those specified in Practice D7869.

9. Report

9.1 Report the following information:

9.1.1 The geographic location for which the estimate of GHUV is calculated.

9.1.1.1 The location should be identified in terms of City, Country, or nominal GPS coordinates, or a combination thereof.

9.1.2 The GHUV estimate calculated in accordance with this practice along with the wavelength range over which the GHUV estimate is obtained.

9.1.2.1 Clearly state whether the estimate is for GHUV(280–400) or GHUV(295–385).

9.1.3 The time period for which the GHUV estimate is calculated (that is, annual, by month, by day or for a custom period).

9.1.4 The source of the GHI data used in the calculation.

9.1.5 The source of the Air Mass coefficient (AM) or solar zenith angle values used in the calculation of GHUV.

TABLE 1 Mean m_i Coefficients to Calculate the GHUV(280–400)/GHI and GHUV(295–385)/GHI Ratios Using Eq 1

	m_4	m_3	m_2	m_1	m_0
GHUV(280-400)/GHI	3.50E-06	-1.37E-04	2.01E-03	-1.19E-02	7.19E-02
GHUV(295-385)/GHI	2.10E-06	-9.51E-05	1.54E-03	-9.70E-03	5.70E-02

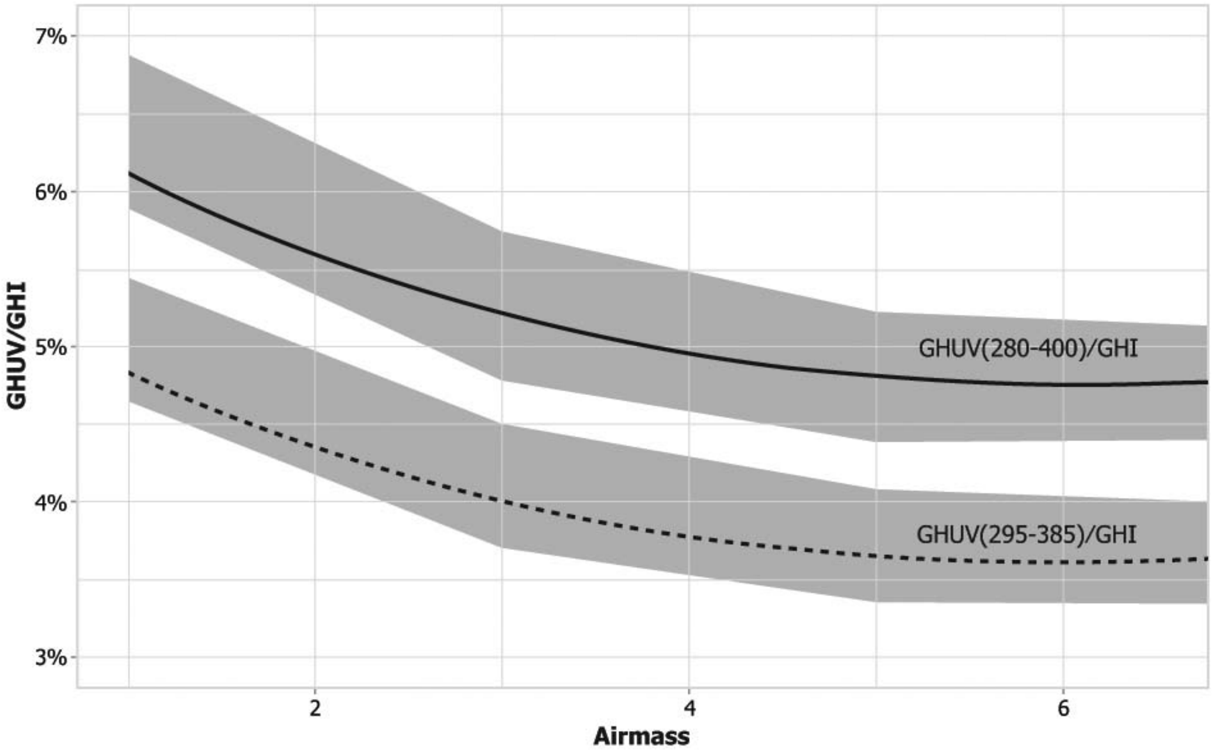

FIG. 1 GHUV/GHI Ratios as a Function of Air Mass, Calculated With the Mean m_i Coefficients for the 280–400 nm Range (Solid Line) and the 295–385 nm Range (Dashed Line); the Bands Around Each Line Represent the Range of Values Calculated for 15 Locations Across Representative Latitudes and Atmospheric Conditions

9.1.5.1 Clearly state whether the AM values are from the NOAA Solar Geometry Calculator or calculated using Eq 2.

10. Precision and Bias

10.1 Fig. 2 illustrates the difference between the GHUV(280–400)/GHI ratios calculated with mean m_i coefficients and measured GHUV/GHI(280–400) values. The accuracy is typically within 8 %.

NOTE 5—The uncertainty of reference spectroradiometers used for solar UV measurements can be up to 7 % (**8**). Therefore, the observed difference in Fig. 2 could move up and down by as much as the uncertainty magnitude of 7 %, for example.

NOTE 6—While the calculations proposed in this practice are derived from a spectral radiation model for clear-sky conditions and then applied to all sky condition, the accuracy of the measurement shown in Fig. 2 is calculated against measured GUV(280–400)/GHI ratios for 4 validation locations listed in Ref (**6**) for all-sky conditions, confirming that the method is applicable for most all sky use cases, and not just clear-sky conditions.

11. Keywords

11.1 Field-exposed products; Location specific UV irradiance; UV irradiance

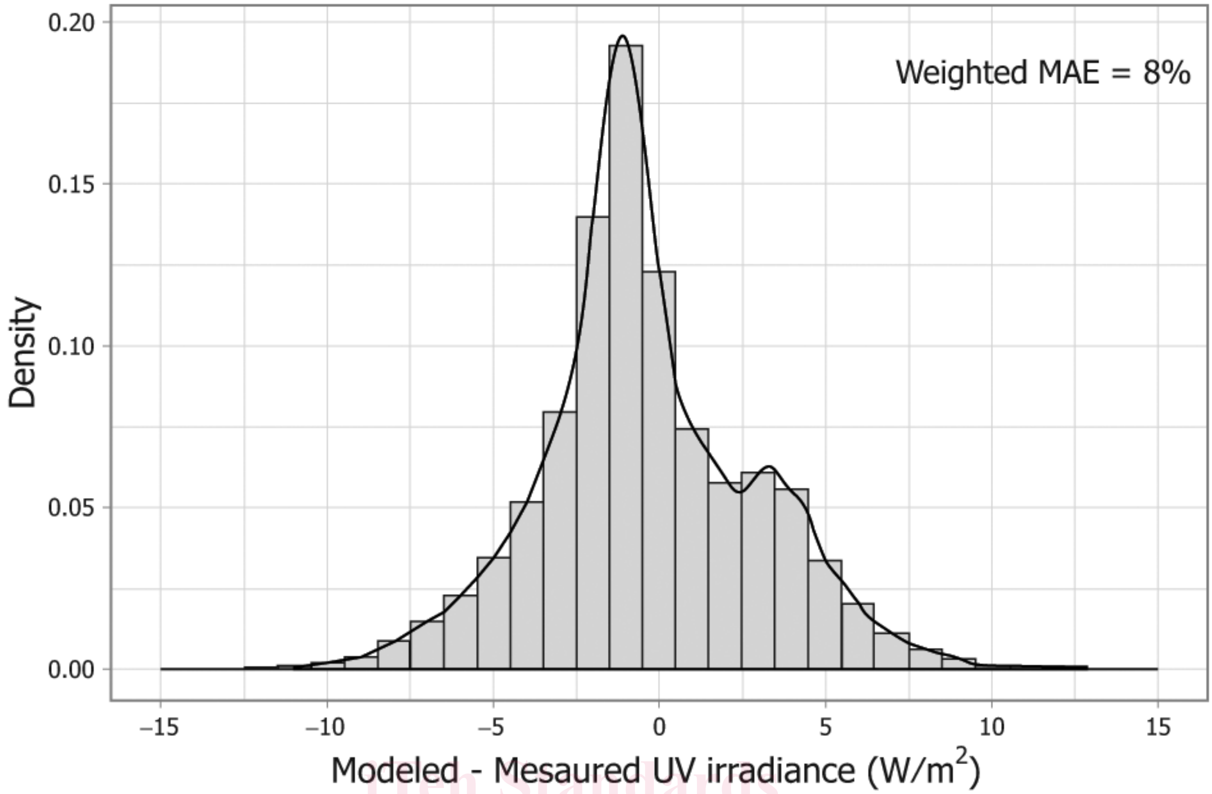

FIG. 2 Accuracy of the GHUV/GHI(280–400) Ratio Calculated With the Mean m_i Coefficients in Table 1 Versus Measured GHUV(280–400)/GHI Ratios for the 4 Validation Locations Listed in Ref (6); the Weighted Mean Absolute Error (MAE) is 8 % and is Due to the Calculation Uncertainty as well as the Measurement Uncertainty Due to Instrument Calibration (8)

APPENDIXES

(Nonmandatory Information)

X1. CALCULATING GHUV/GHI FOR LOCATIONS FEATURED IN THE NATIONAL SOLAR RADIATION DATABASE (NSRDB)

X1.1 If the location of interest to estimate GHUV is covered in the NREL's NSRDB, the method described in this practice is already fully implemented in the database. Therefore, the data can be downloaded directly using the following steps:

X1.1.1 Go to https://nsrdb.nrel.gov.

X1.1.2 Click NSRDB viewer – https://maps.nrel.gov/nsrdb-viewer/.

X1.1.3 Click "Download Data" (top left) and choose "NSRDB Data Download (Point)" or "NSRDB Data Download (Box)" and then select/click the area of interest on the map. Alternatively, use select zoom to location option (top right) and enter an address, city, state, zip, or latitude and longitude of area of interest.

X1.1.4 Fill the data download information form.

X1.1.5 Then follow the data download wizard to download the GHUV data (Fig. X1.1).

X1.1.6 Alternatively, the data may be downloaded programmatically using application programming interface (API). See instructions at https://developer.nrel.gov/docs/solar/nsrdb/.