Reflected solar radiation from horizontal, vertical and inclined surfaces: Ultraviolet and visible spectral and broadband behaviour due to solar zenith angle, orientation and surface type

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Abstract

Ultraviolet (UV) radiation affects human life and UV exposure is a significant everyday factor that individuals must be aware of to ensure minimal damaging biological effects to themselves. UV exposure is affected by many complex factors. Albedo is one factor, involving reflection from flat surfaces. Albedo is defined as the ratio of reflected (upwelling) irradiance to incident (downwelling) irradiance and is generally accepted only for horizontal surfaces. Incident irradiance on a non horizontal surface from a variety of incident angles may cause the reflectivity can change. Assumptions about the reflectivity of a vertical surface are frequently made for a variety of purposes but rarely quantified. As urban structures are dominated by vertical surfaces, using albedo to estimate influence on UV exposure is limiting when incident (downwelling) irradiance is not normal to the surface. Changes to the incident angle are affected by the solar zenith angle, surface position and orientation and surface type. A new characteristic describing reflection from a surface has been used. The ratio of reflected irradiance (from any surface position of vertical, horizontal or inclined) to global (or downwelling) irradiance (RRG) has been calculated for a variety of metal building surfaces in winter time in the southern

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hemisphere for both UV and visible radiation spectrum, with special attention to RRG in the UV spectrum. The results show that the RRG due to a vertical surface can exceed the RRG due to a horizontal surface, at smaller solar zenith angles as well as large solar zenith angles.

The RRG shows variability in reflective capacities of surface according to the above mentioned factors and present a more realistic influence on UV exposure than albedo for future investigations. Errors in measuring RRG at large solar zenith angles is explored, which equally highlights the errors in albedo measurement at large solar zenith angles.

Introduction

Exposure to biologically effective ultraviolet (UV) radiation can be beneficial to human health in the form of initiating pre-vitamin D_3 formation [1] and detrimental; such as erythema, skin cancer, ocular damage and more [2]. UV exposure is specific to the formation of the above health effects and much research has been conducted to measure and model UV exposure. UV radiation is influenced by (and UV exposure modelling must take into account) many atmospheric factors; including solar zenith angle, altitude, latitude, ozone, clouds, aerosols, albedo (reflectivity) [3,4] and personal factors; including occupation and personal behaviour [5-8].

Albedo is defined as the ratio of reflected (upwelling) irradiance to incident (down welling) irradiance for horizontal surfaces [9]. A surface that varies from a horizontal position but is still exposed to downwelling irradiance (to be referred to as global irradiance in this paper) can still produce reflected irradiance from the surface to the immediate environment. Due to the nature of the definition of albedo, this type of reflectivity cannot be assumed to be equivalent to albedo as it is dependent on the surface orientation and direction, solar zenith angle and type of surface, all of which contribute changes in the angle of incident UV radiation. If albedo is used to approximate this type of reflectivity for non horizontal surfaces, then contributions of such reflectivity to UV exposures to an individual could either be underestimated or overestimated. In the complex nature of the human environment, particularly urban environments which are dominated by vertical surfaces, understanding the interaction of reflected irradiance from vertical surfaces (as well as horizontal and inclined) will be important for health and safety issues for outdoor workers.

Previous work on reflectivity includes the investigation of the albedo of horizontal surfaces [9-12] as well as inclined surfaces such as snow covered mountain sides [13-

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14]. Irradiances on inclined surfaces affected by surrounding albedo have been previously explored [15-17]. Investigation of the biological effectiveness of the contribution to personal UV exposures due to the albedo of different horizontal and inclined surfaces has been investigated [18-20]. These effects are particularly important for outdoor workers' who should be aware of the contribution to UV exposures from such surfaces due to everyday working conditions [21]. The Guidance Note for the Protection of Workers from the Ultraviolet Radiation in Sunlight [21], specifies that workers be aware of the reflection of shiny metallic surfaces in the worker's vicinity. However, little information is available about the reflective capabilities of global UV irradiances from vertical surfaces in the vicinity of outdoor workers. The albedo of vertical surfaces has been briefly investigated for glass surfaces, along with the effect on diffuse UV due to the presence of walls [20]. Other studies mention albedo due to vertical surfaces in terms of modelling UV exposure but do not define the type of reflection of the global radiation from that surface [22]. Global irradiance will vary according to the factors that influence the incidence angle of UV irradiance on a surface. Investigation of the UV irradiance received on vertical surfaces has been carried out [11,19,23]. Webb et al. [24] determined a relationship between vertical and horizontal irradiances. This research found that when solar zenith angles are large and the vertical surface is facing the direction of the sun, the vertical surface will receive more irradiance than a horizontal surface. The study for horizontal albedo of roofing material by Lester and Parisi [18] shows high albedo recorded for shiny and coated horizontal surfaces, but does not consider vertical surfaces. However, in many industrial work sites, it can be commonplace to use the metal roof cladding as wall cladding. In urban residential areas, coated metal surfaces are used for fencing and both coated and shiny surfaces can be used for

garden sheds or garages. This paper will compare the ratio of reflected irradiance to global irradiance (RRG) due to vertical and inclined surfaces to the albedo of a horizontal surface, by considering both the spectral and broadband RRG for visible and UV radiation. The paper will consider the variations of RRG due to solar zenith angle, orientation of the vertical plane and different metal surface types. Since albedo is quantitatively the same as the RRG on a horizontal surface, the term RRG will be used instead of albedo, unless referring specifically to referenced albedo measurements.

Methodology

The measurements were carried out on an archery field at the University of Southern Queensland, Toowoomba, Australia (27.5° S, 151.9° E). A metal frame was constructed to support a 1 m × 1 m size vertical sheet, of either Trimclad (trapezoidal) or corrugated sheet metal, to simulate the exterior wall of a building or a fence. A secondary piece of sheet metal of the same size was attached to the other side of this metal frame, inclined at 35º from the horizontal, simulating the sheet metal on the roof of a building. Both sheets were separated by the frame with sufficient distance between each sheet to prevent shading.

Eight types of Trimclad metal sheeting and two types of corrugated metal sheeting were used (supplied by Metroll, Toowoomba). The corrugated metal sheets consisted of one Zincalume (steel coated with zinc and aluminium) surface and one Colorbond cream coloured surface. The distance between the ridges on the corrugated iron waves was 7.8 cm and the height difference between a trough and a peak was 1.7 cm. The Trimclad metal sheeting consisted of one Zincalume surface, six Colorbond coated surfaces (cream, beige, pale green, blue, dark red and black) and one Zincalume

surface coated with "It's so cool" exterior paint (supplied by The Australian Insulation Super Store, Brisbane). The height difference between the top and bottom of the profile of the Trimclad was 2.9 cm. The distance between the centres of the high ridges was 19 cm. Both sheet types have the ridges equally spaced across the surface and are symmetrical. The surface ridges are aligned top to bottom for inclined and vertical surfaces which holds with general building practices, and north to south for the horizontal surface.

Measurements of the spectral irradiances were made with an EPP2000 spectrometer (StellarNet, Florida, USA) with a detector based on a CCD array with a concave holographic grating with a groove density of 300 g/mm. The spectrometer has a slit width of 25 µm to give a resolution of less than 1 nm. Wavelength and irradiance calibration of the EPP2000 was undertaken by employing the 365 nm mercury spectral line and a 150 Watt quartz halogen lamp with calibration traceable to the National Physical Laboratory, UK standard. A two meter fibre optic cable connects a cosine receptor to the input of the housing for the array. The EPP2000 measured spectral irradiance from 300 nm to 700 nm in 0.5 nm steps. The integration time was 24 ms and averaged over 25 scans. The receptor was held in place using a lab stand with a 0.5 m arm and clamp. The arm held the receptor away from the main body of the lab stand, therefore reducing the amount of shadow that might fall on the metal sheeting during measurement. The lab stand, arm and clamp were adjustable so that the RRG of the horizontal, vertical and inclined surfaces was recorded at 0.5 m from the surface of the metal sheeting, with the sensor facing along the normal to each type of surface. The distance of 0.5 m was chosen because this would be the approximate arm's length distance a person would be from the metal surface if they were working in a building situation, such as construction of a wall or roof. The distance of 0.5 m

was chosen using tests that were carried out to determine if the skyview beyond the sheet would affect the measurements. The test compared the reflectivity at distances that were close enough to the sheet so that the cosine receptor would not receive any irradiance other than that from the sheet, to that at longer distances. The distances employed were 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.5 m and 1.0 m. It was found that for surfaces facing the sun, the skyview had little effect on the RRG recorded. The distance the sensor was from the surface did have an effect, the further from the surface, the lower the RRG was recorded. Only on surfaces that were facing away from the sun did the skyview have an effect. For these surfaces, when direct sunlight fell on the sensor, the data collected was discarded when it was apparent that an RRG of above 1.0 was not possible. Thus the decision to choose a distance of 0.5 m from the surface was the most practical distance for construction workers, for this current study.

To account for the solar zenith angle (SZA) four series of measurements were carried out for a SZA range over a day between 35.3º and 73.4º for one sheet metal type. Early morning measurements began at 8 am local time, mid-morning measurements began at 10 am, midday measurements at noon and mid-afternoon measurements at 2 pm. Each series of measurements lasted approximately forty minutes. Each measurement made had the local time recorded, so that the appropriate SZA could be calculated.

In order to be consistent with the orientation, the metal frame was placed so that the vertical face was oriented towards geographical north initially (and therefore the inclined face was oriented to the south).The horizontal sheet was placed a short distance away from the metal frame to prevent shading. The metal frame was rotated and measured with the vertical face oriented to each of the west, south and east (the

inclined face was oriented to the east, north and west). In the southern hemisphere, the north facing surface receives the most UV irradiance compared to surfaces facing west, south and east.

The spectral RRG was measured by recording the global spectral irradiance on a horizontal plane, then recording the reflected spectral irradiance for a given surface and taking the ratio of the spectral irradiances at each wavelength. To measure the reflected spectral irradiance, the EPP receiver was oriented to the normal of the reflecting surface at an average distance of 0.5 m. Each different oriented surface was measured for global spectra and reflected spectra, at each position (vertical, horizontal and inclined) throughout the day. Each measurement was repeated to allow averaging of the results.

The average RRG_{UVB} was determined by integrating the spectral data from 300 nm to 320 nm in 0.5 nm increments for each reflected and global spectral irradiance measurement before calculating the ratio. The RRG was then averaged according to the influencing factors: surface type, position, orientation and SZA.

Shading to the sensor due to the surface itself did not occur, due to the measurement procedure. The affect of shading to the RRG was not explored as it was outside the scope of the current investigation. The effect of shading will be a suitable future extension of this investigation.

Results

Spectral RRG due to surface type and position

The spectral behaviour of the RRG_{UV} and $RRG_{visible}$ for five of the eight Trimclad surfaces is shown in Figure 1 for a SZA range of 35.3º to 47.6º. The three colours not included had the same spectral RRG as already represented surfaces and will be

discussed later. The cream and Zincalume corrugated surfaces produced very similar spectral RRG as the cream and Zincalume Trimclad surfaces.

The Zincalume vertical metal surface is the only type that reflects uniformly in the UV wavelengths at 0.30 RRG_{UV} (at a SZA range of 35.3º to 47.6º), which is significantly different to that of the other surfaces in the UV. An RRG_{UV} of 0.30 is significant, especially when considered in comparison to albedo due to natural horizontal surfaces, such as grass: 0.016 to 0.02 (at 300 nm and 400 nm respectively) [10] and sand: 0.09 erythemal albedo to 0.24 average UV albedo [12] and 0.14 to 0.24 (300 nm to 400 nm respectively) [10]. The coated metal surfaces (both Colorbond and Insultec painted) have the same spectral RRG_{UV} , except for the black surface which is lower.

The white based surfaces (Insultec, cream Colorbond and pale green Colorbond) have a higher RRG_{UV} of 0.1 to 0.2 in the shorter UV wavelengths (the spectral RRG_{UV} decreasing as wavelengths increase) until about 380 nm, where it then starts to increase at approximately 380 nm and into the visible spectrum. This increase is up to 0.15 for the Insultec and cream surfaces. The maximum $RRG_{visible}$ occurs within the 500 nm to 600 nm range, for all surfaces except the black. The beige Trimclad surface had the same spectral RRG as the cream Trimclad surface, while the red and blue Trimclad surfaces had the same spectral RRG as the black Trimclad surface. This may be attributed to red and blue being dark based colours. Black Trimclad has the most consistent RRG across the UV and visible spectrums for a vertical surface, but the spectral RRG decreases over increasing wavelengths for the visible spectrum. The low $RRG_{visible}$ is explained by the tendency of dark surfaces to absorb radiation rather than reflect.

Figure 2 shows four types of metal surfaces, (a) Zincalume and black Trimclad and (b) cream and pale green Trimclad, at SZAs of 35.3º to 47.6º during winter noon, for horizontal, vertical and inclined planes. The Zincalume surface reveals that the spectral RRG_{UV} on a vertical plane is higher by 0.02 to 0.04 than the spectral RRG_{UV} on the horizontal plane. Additionally the spectral RRG_{UV} due to the inclined surface is higher than the spectral RRG_{UV} due to the vertical plane by about 0.1. This is a large variance from the spectral RRG_{UV} due to the horizontal plane. The black surface has a spectral RRG_{UV} on the vertical plane at 0.01 to 0.06 higher than the horizontal plane. This is also shown to occur for cream and pale green surfaces. This behaviour was also observed on the beige, blue and red Trimclad and cream corrugated surfaces. The only surfaces where this was not predominantly observed was the Insultec Trimclad and the Zincalume corrugated, where both vertical and horizontal surfaces appeared to have the same spectral RRG in the UV spectrum up until 380 nm. The visible spectrum was not observed to have the same behaviour, with the horizontal spectral $RRG_{visible}$ greater than vertical spectral $RRG_{visible}$ for all surfaces except for the beige, red and blue Trimclad surfaces.

Spectral RRG due to SZA

Changing the time of day and therefore the SZA shows very different spectral RRG behaviour, particularly for the Zincalume surface. Figure 3 (a) shows measurements at 72.6º, 72.2º, 53.5º, 46.2º and 55.4º for vertical Zincalume Trimclad on a north facing vertical plane. Early morning reveals the rapid change as the SZA decreases. The spectral RRG_{UV} values at 72º are larger than 0.5 over all wavelengths.

RRG values of 1.0 or above 1.0 are indicated in Figure 3. However, it is unlikely that these are accurate RRG values. Analysis of the direct and diffuse UV component of

global irradiance values at large solar zenith angles has been carried out [25-26] and these components of the global irradiance can affect RRG values at particularly large SZA. The global irradiance is measured as the down-welling irradiance from the hemispherical sky-view above the receptor. Depending on the SZA, this global irradiance contains little to no direct UV (at large SZAs) and can be entirely made up of diffuse irradiance [25]. A measurement from a reflective surface facing the sun at large SZA is likely to record this same diffuse measurement as the global irradiance measurement, and additionally a reflected direct UV component. If the direct UV component is measured as a part of the reflective component, but not of the global component of a total RRG measurement, the RRG result will appear to be 1.0 or greater than 1.0. This is a wavelength specific characteristic. As the SZA decreases, the direct UV content of the global irradiance increases [26] and this effect observed at large SZAs slowly diminishes.

Spectral RRG due to orientation

The influence of the solar azimuth on the spectral RRG_{UV} of a vertical Zincalume Trimclad surface is shown in Figure 4. Figure 4 (a) shows the spectral RRG_{UV} for north, west, south and east for mid morning (SZA range of 54º to 49º), while Figure 4(b) shows the spectral RRG_{UV} for north, west, south and east for mid afternoon (SZA range of 54.9º to 61.5º). For mid morning, the maximum spectral RRG_{UV} occurs on the north vertical facing side, while mid afternoon, maximum spectral RRG_{UV} occurs on the west vertical facing side. In general, when the sun is not facing the vertical plane, the spectral RRG_{UV} remains the same for each orientation.

Average RRG for surface type and position

Figure 5 displays the average RRG_{UVB} (the average of the RRG_{UV} measured for each 0.5 nm step from 300 nm to 320 nm) for a Zincalume Trimclad surface, for the entire day of orientation, position and SZA variations. The early morning RRG_{UVB} measurements (SZA range of 73.4º to 63.9º) are mostly greater than other times of the day (mid morning: 54º to 49º, midday: 46.1º to 47.6º and mid afternoon: 54.9º to 61.5º). The early morning west vertical RRG_{UVB} values are not available due to the sensor being exposed to direct sunlight at that time. This was due to the azimuth of the sun rather than the height of the vertical plane not providing shade to the sensor. The same occurred for most south vertical plane RRG_{UVB} measurements. The midday east vertical RRG_{UVB} is missing due to the height of the vertical plane resulting in no shade to the sensor.

The greatest average RRG_{UVB} is recorded on the north inclined plane in the early morning. The inclined planes for the west and the north have the largest RRG_{UVB}, while the south and the east inclined RRG_{UVB} are still effective at greater than 0.15. There is greater variation between early morning and midday RRG_{UVB} on inclined planes, which is due to the SZA variation. Table 1 shows the average RRG_{UVB} for all metal surface types, comparing overall, vertical, horizontal and inclined surfaces.

Discussion

The RRG_{UV} is a significant characteristic of a reflecting surface. The RRG_{UV} is not the same as UV albedo. UV albedo is a useful tool in estimating increases or decreases to total UV exposure, but only for situations where the incoming radiation consisting of both direct and diffuse UV radiation is incident on a surface that is normal to this radiation, generally a horizontal surface. However, the content of direct and diffuse UV in global radiation changes according to SZA and azimuth, as well as

surface type, position and orientation. For example, an industrial shed is being built with a shiny metal, with the entrance and main outside work area facing north. What effect does this wall have on the UV exposure of a worker at different times of the day? Albedo is no longer representative of the reflective capacity of a surface oriented at a position that does not receive both direct and diffuse UV radiation. A vertical surface with the sun at a small SZA would receive very little direct UV, but would still reflect diffuse UV. At the same SZA a horizontal surface will easily reflect both direct and diffuse UV radiation as they are both incident on the horizontal surface. To effectively quantify the influence of the reflective capacity of a surface at positions other than the horizontal, the RRG $_{UV}$ has been defined and employed in this paper.

RRG$_{UV}$ due to surface type and position

Figures 1 and 2 show the spectral distribution of the RRG$_{UV}$ from a Zincalume Trimclad surface. There is some photon noise present at the shorter wavelengths, but this does not affect the overall spectral distribution. The spectral RRG$_{UV}$ measured due to vertical surfaces is in agreement with the work of Lester and Parisi [18] in which it was found that galvanised (zinc coated steel) corrugated metal at 305nm had an albedo of 0.27. The measured spectral RRG$_{UV}$ is approximately 0.3 at most wavelengths in Figure 1, slightly higher than the albedo measured by Lester and Parisi.

The Insultec coated surface can be compared to a previous study by Parker et al. [27], in which the UV reflectance was measured as 0.184 for a small 0.1 m × 0.1 m sample. Table 1 shows the average value of 0.19, although the spectral data in Figure 1 suggests the RRG$_{UV}$ may actually be much lower than that measured by Parker et al.

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The authors of that study caution that this may be variable due to the nature of the measurements made.

Figure 2 shows vertical surfaces with greater spectral RRG_{UV} than horizontal surfaces, and this is replicated by all other surface types (not shown except for the beige, red and blue surfaces: these three surfaces have the same RRG_{UV} for horizontal and vertical surfaces at the same SZA).

The Zincalume corrugated surface (not shown) has a similar spectral RRG_{UV} on a vertical plane as the Zincalume Trimclad surface and the averages observed in Table 1 suggest there is little difference between sheet metal structure, however the averages for cream Trimclad and cream corrugated surfaces are different, with the corrugated cream surface reflecting an average of ten percent less than the cream Trimclad. Coulson and Reynolds [11] suggests the structure of a surface that has many interstices is less capable at reflecting because of the likelihood of trapping photons within the structure itself (due to the ridges in the metal), however this does not explain why this is not observed for both metal structure types in a Zincalume finish. Perhaps in this case the shiny surface exceeds the ability of the corrugated structure to trap more photons than the Trimclad and therefore both the Trimclad and corrugated surfaces behave in the same reflecting manner. The metal sheeting is new and has not been affected by the weather and environment. A Zincalume metal sheeting that has been affected by time and environment may be very different in spectral and average RRG_{UV} characteristics.

The zincalume surfaces appear to have the largest RRG_{UV} out of all the surfaces. This may be due to the shiny smooth finish of the surface. Roughness lowers the reflectance of surfaces [27] and painted or coated surfaces may be rougher at the particle level than steel. The expected RRG_{UV} values for vertical surfaces are

suggested by Heisler and Grant [20], who state that most clean metals free of oxide and tarnish have an albedo of 0.3 to 0.55 within the UVB waveband.

RRG_{UV} due to SZA and solar azimuth

The position of the early morning sun means that direct UV is positioned to fall more directly on the north facing vertical plane, causing maximum reflection of the incident UV to the detector for a north facing orientation. A factor that may contribute to large RRG_{UV} values for large SZA in the early mornings is the lack of atmospheric interference from a clear sky, where condensation and particulate matter has fallen overnight and has not yet evaporated. By mid morning the SZA is nearly 20º less than the early morning values and the spectral RRG_{UV} has also decreased, averaging just over 0.3. At midday, the spectral RRG_{UV} remains around 0.3 however, the mid afternoon spectral RRG_{UV} drops below 0.3, despite being approximately at the same SZA as the mid morning value. This decrease is due to the change in azimuth from morning to afternoon, where the direct UV falling on the vertical surface has decreased due to the westerly progression of the sun through the sky. This was also observed by Webb et al. [24] when investigating irradiances falling on vertical planes. Figure 3 (b) on a north facing black Trimclad surface, shows the behaviour of the Zincalume Trimclad is not similar to that of the dark coated Colorbond surface, where the minimum spectral RRG observed is that at a SZA of 36.8º, while the afternoon and morning spectral RRG are somewhat greater.

Investigation of the cream, Insultec and pale green Trimclad surfaces, showed that the RRG_{UV} at a large SZA was always greater than RRG_{UV} values at smaller SZA, and that SZA values below 50º and above 35.3° tended to show the same spectral RRG_{UV}

throughout the day, with just small variation between morning, midday and midafternoon values.

Comparing Figures 2 and 3 the vertical and horizontal spectral RRG_{UV} at large SZA, indicate that the vertical spectral RRG_{UV} is much larger than the horizontal spectral RRG_{UV} for most metal surfaces. For large SZA, a first glance at the results suggest the vertical spectral RRG_{UV} is almost double the horizontal spectral UV albedo for Zincalume (0.5 and 0.3 respectively) and light coloured Colorbond surfaces (0.2 and 0.1), and more than double for dark Colorbond surfaces (0.15 and 0.05). However, as outlined in the results, the RRG_{UV} values at large SZA may be overestimated, due to the components of the global UV irradiance being dominated by diffuse UV irradiance and very little direct UV irradiance. Thus, when the reflected UV is measured for a vertical surface at a large SZA oriented towards the sun, it is possible there is more direct UV present in the reflected UV irradiance than in the global irradiance. Hence the tendency to find some RRG_{UV} values greater than one at large SZA with surfaces oriented towards the sun. For dark coated surfaces, whilst the RRG_{UV} due to a vertical surface may be small, these are still considerably larger than the RRG_{UV} due to a horizontal surface. The same overestimation is likely to be occurring with even the dark coated surfaces, even if the values are not unrealistic. Comparing the RRG_{UVB} in Table 1 for horizontal and vertical surfaces suggests this may be a possibility where for even dark coated surfaces the RRG for vertical surfaces is quite large. Comparatively, the zincalume surfaces have very little difference between average horizontal and vertical RRG, so it is uncertain how much overestimation really is occurring. It is possible that RRG values at large SZA will be negligible in influencing UV exposure to individuals, due to the attenuation of UV wavelengths at that time of day. Weihs et al., [13] found albedo values for inclined

ground surfaces greater than 1.0 but only accounted for these values by concluding

that directionality was the cause but did not explain how to account for it. It is

interesting to note their albedo values were found for a SZA of 49°, a SZA much

smaller than found in this study for RRG_{UV} values greater than 1.0. Altitude would

have had a significant influence on their data and may explain the contrast to the data

found in this study, as well as the different techniques used in measuring the albedo.

To account for the RRG_{UV} at large SZA, further research will include global

irradiance measurements to be investigated with the sensor directed towards the sun in

addition to the downwelling (global) irradiance measurement, which is expected to

show albedo or RRG_{UV} values greater than 1.0 are overestimations.

Average RRG_{UV}

Figure 5 is just one surface type of the ten investigated, yet it shows an interesting

effect in the RRG_{UV} due to a horizontal surface. Despite the changing SZA, there is

less variation in RRG_{UV} due to a horizontal surface than due to a vertical surface and

the overall averages are also slightly less, even though the incident angle of the direct

UV irradiance as a component of the global irradiance is changing. Additionally, the

RRG_{UV} at large SZA due to a horizontal surface is larger than at noon. However, as in

the case of the overestimation of RRG_{UV} for vertical surfaces at large SZA, the

RRG_{UV} for horizontal surfaces at the same SZA may also be overestimated, with the

global irradiance unlikely to account for all the direct UV irradiance that does fall on

the horizontal surface. This would also be true for inclined surfaces at large SZA.

Taking all the daily data for each of the surface types and calculating a single

RRG_{UVB} for all data, all horizontal data, all vertical data and all inclined data, it has

been found the possible overestimation for large SZA is likely to have led to an

overestimation of a daily average. This is apparent in the coated surface variation between the averages of horizontal and vertical RRG_{UVB} where vertical RRG_{UVB} are more than double the RRG_{UVB} on a horizontal surface. The zincalume surfaces do not show this trend, and despite the earlier discussion on reflective capacity of zincalume surfaces, it does not answer why the RRG_{UVB} for horizontal and vertical surfaces should be so similar but not for the coated surfaces. The only other possibility of explanation is the behaviour of the reflection itself, meaning specular reflection (reflecting at the boundary of the surface) or diffuse reflection (reflecting from particles below the surface). Until this overestimation is calculated, the average daily values of RRG_{UVB} are not likely to provide accurate information for current use. What is apparent from Figure 5, despite the overestimation of RRG_{UV} values at large SZA, there appears to be a relationship between the SZA, the position of the surface, and the orientation surface and the measured RRG_{UV} values for this surface type. Further measurements will be carried out to determine a more accurate relationship between the RRG_{UV} and the influencing factors. Current modelling studies that calculate albedo in urban environments may benefit from calculating RRG instead of albedo. An example of such a model is that reported by Chimklai, Hagishima and Tanimoto [29] that modelled albedo for vertical surfaces, and found there was still differences between the observed albedo and modelled albedo despite excellent attention to detail in influencing factors. Additionally, the use of RRG instead of albedo could be used to produce more accurate models that determine UV exposure in urban environments. Extension of this work will include measuring the effects on total UV exposure to humans due to the presence of a vertical, inclined or horizontal surface.

Conclusions

For outdoor workers (such as construction workers) who spend time in the vicinity of vertical, horizontal or inclined metal surfaces, the RRG_{UV} may lead to an increase in UV exposure, particularly for those metal surfaces with a galvanised or Zincalume finish. Vertical metal planes facing the sun have higher RRG_{UV} at large SZAs than horizontal metal planes. Early morning or late afternoon sun may have more effect on a person if they are standing in the vicinity of such a surface, but UV exposure could equally be negligible due to attenuation at these solar zenith angles. The most common of these vertical surfaces in every day life are Zincalume or green Colorbond surfaces, such as garden sheds and residential fencing. A person going about their usual activities outside in the garden could increase their overall UV exposure, if they are working in the vicinity of this type of vertical plane.

Prevention of overexposure of UV radiation to the everyday person, can be achieved by ensuring the person wears sun protective clothing and applies sunscreen, as well as hat and glasses. Workers in the construction industry should be advised of the RRG_{UV} of metal surfaces on vertical, horizontal and inclined planes and advised to protect themselves according to the guidelines outlined in the Guidance Note for the Protection of Workers from the ultraviolet radiation in sunlight [21].

This research has shown that in many cases the RRG_{UV} from vertical metallic surfaces is not equivalent to the RRG_{UV} from a horizontal metallic surface (also known as albedo) for a spectral distribution. RRG_{UV} from a vertical metallic surface can exceed RRG_{UV} from a horizontal metallic surface and is dependent on solar zenith angle, orientation and surface type. This may have considerable impact on UV exposure applications such as modelling, and direct impact on workers in the building industry and even everyday life.

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Figure 1 – Spectral RRG of various vertical Trimclad surfaces at a SZA range of 35.5º to 47.6º.

Figure 2 – (a) Spectral RRG at SZA range of 36.7º to 47.6º for horizontal, vertical and inclined surfaces for black and Zincalume Trimclad metal surfaces and (b) Spectral RRG at SZA range of 35.3º to 45.1º for horizontal, vertical and inclined surfaces for cream and pale green Trimclad metal surfaces.

Figure 3 – (a) Spectral RRG_{UV} for varying SZAs on a north facing vertical Zincalume Trimclad surface. The spectral RRG_{UV} for SZA of 55.4° is less than that of 53.5º due to the position of the sun in the west of north rather than east of north.
(b) Spectral RRG_{UV} for varying SZAs on a north facing black Trimclad surface. The minimum RRG_{UV} is observed at 36.8º.

Figure 4 - (a) Spectral RRG_{UV} of vertical Zincalume Trimclad surface, according to the sheet metal face orientation of north, west, south and east. The SZA range is 54º to 49º during mid-morning measurements. (b) Spectral RRG_{UV} of vertical Zincalume Trimclad surface, according to the sheet metal face orientation. The SZA range is 54.9º to 61.5º during mid-afternoon measurements.

Figure 5 – Average RRG_{UVB} (from 300 nm to 320 nm) albedo for Zincalume surfaces at various orientations, positions and SZA.

Table 1 – Comparison of average RRG_{UVB} radiation over all metal surface types and all SZAs.
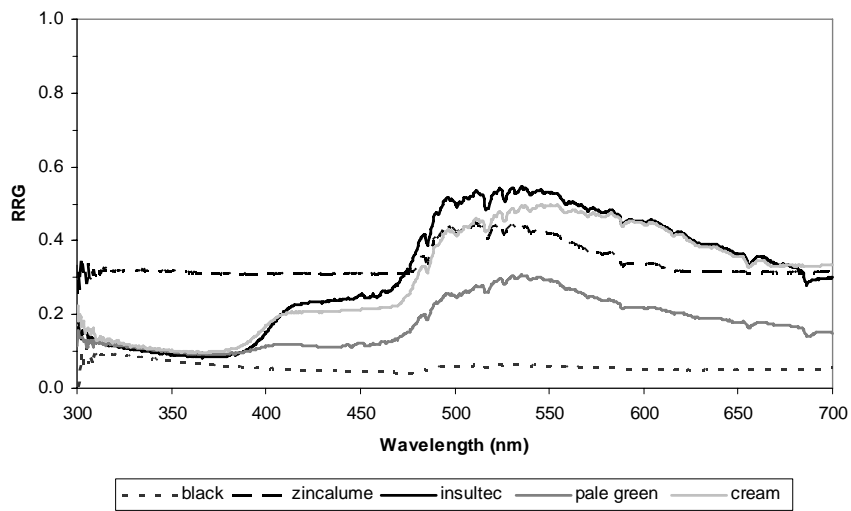
Figures

Figure 1 – Spectral RRG of various vertical Trimclad surfaces at a SZA range of 35.5°
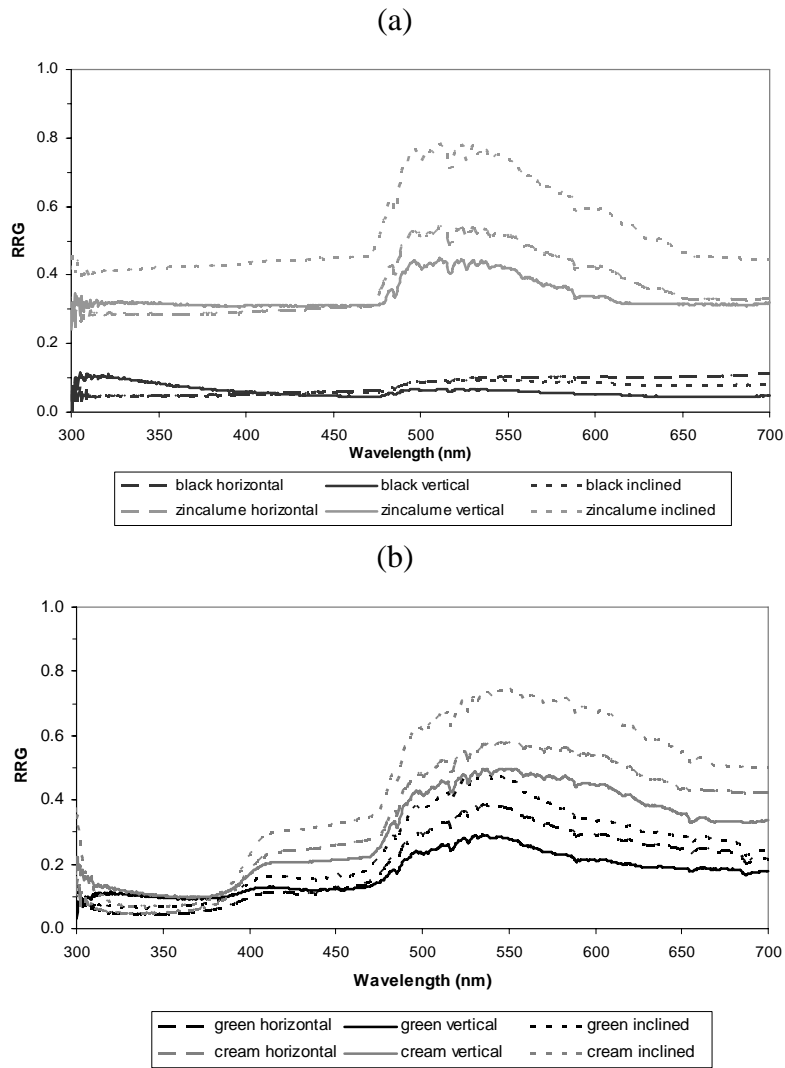to 47.6°.

(a)

(b)

Figure 2 – (a) Spectral RRG at SZA range of 36.7º to 47.6º for horizontal, vertical and inclined surfaces for black and Zincalume Trimclad metal surfaces and (b) Spectral RRG at SZA range of 35.3º to 45.1º for horizontal, vertical and inclined surfaces for cream and pale green Trimclad metal surfaces
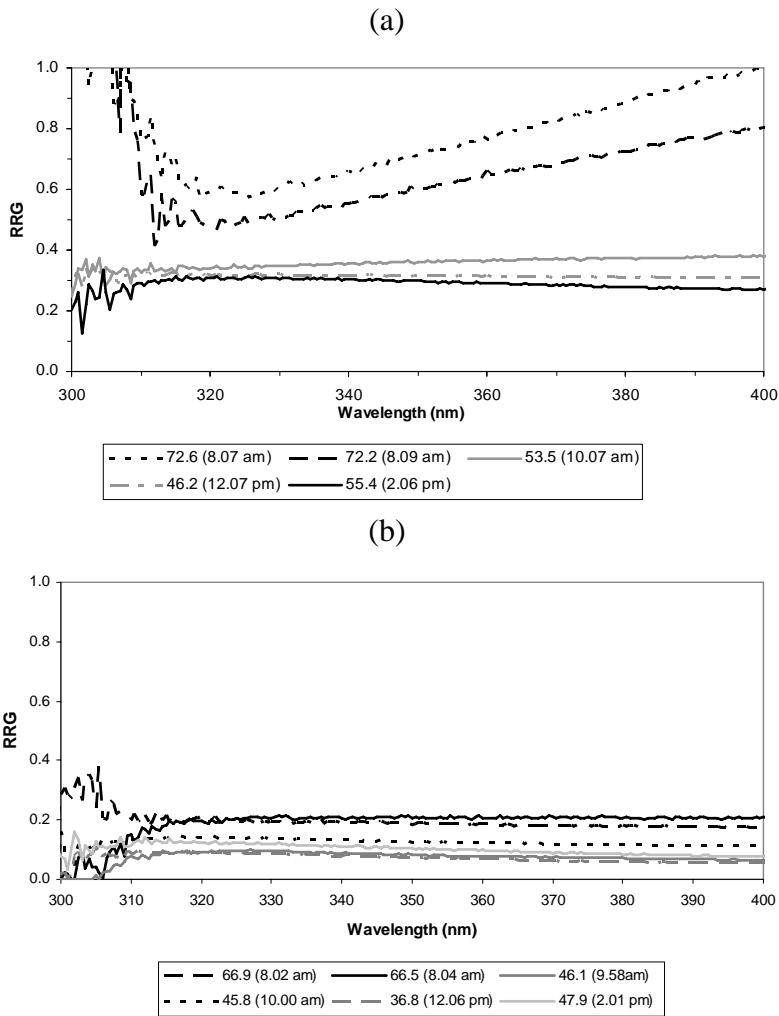
(a)

(b)

Figure 3 – (a) Spectral RRG_{UV} for varying SZAs on a north facing vertical Zincalume Trimclad surface. The spectral RRG_{UV} for SZA of 55.4° is less than that of 53.5° due to the position of the sun in the west of north rather than east of north.
(b) Spectral RRG_{UV} for varying SZAs on a north facing black Trimclad surface. The minimum RRG_{UV} is observed at 36.8°.
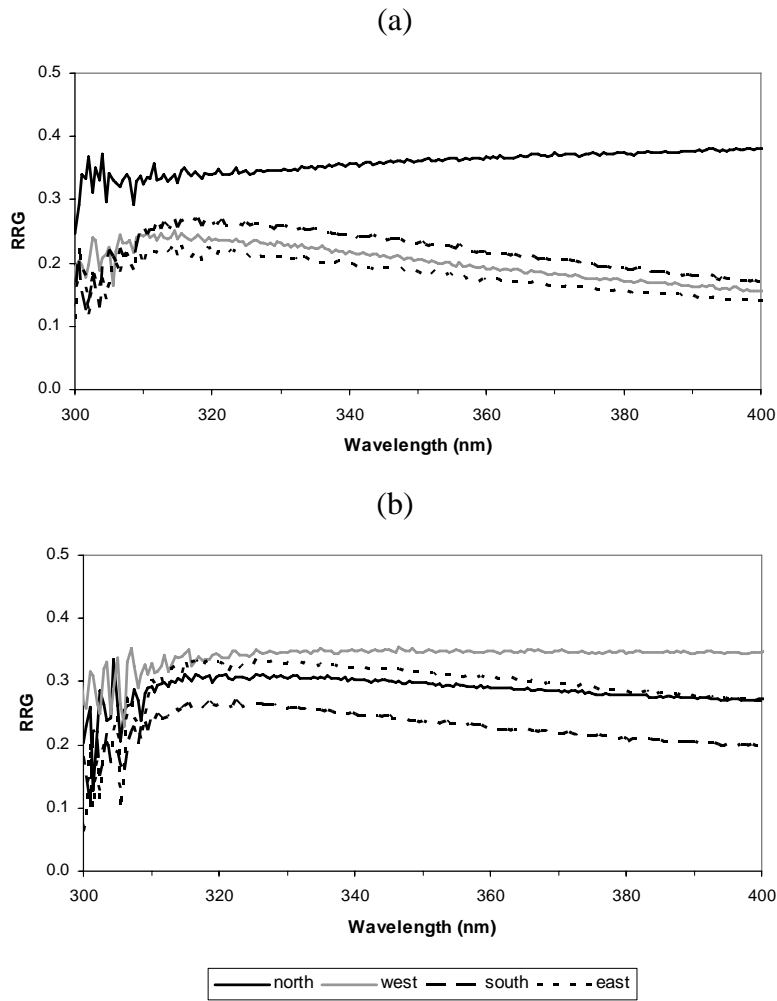
(a)

(b)

Figure 4 - (a) Spectral RRG$_{UV}$ of vertical Zincalume Trimclad surface, according to the sheet metal face orientation of north, west, south and east. The SZA range is 54º to 49º during mid-morning measurements. (b) Spectral RRG$_{UV}$ of vertical Zincalume Trimclad surface, according to the sheet metal face orientation. The SZA range is 54.9º to 61.5º during mid-afternoon measurements.
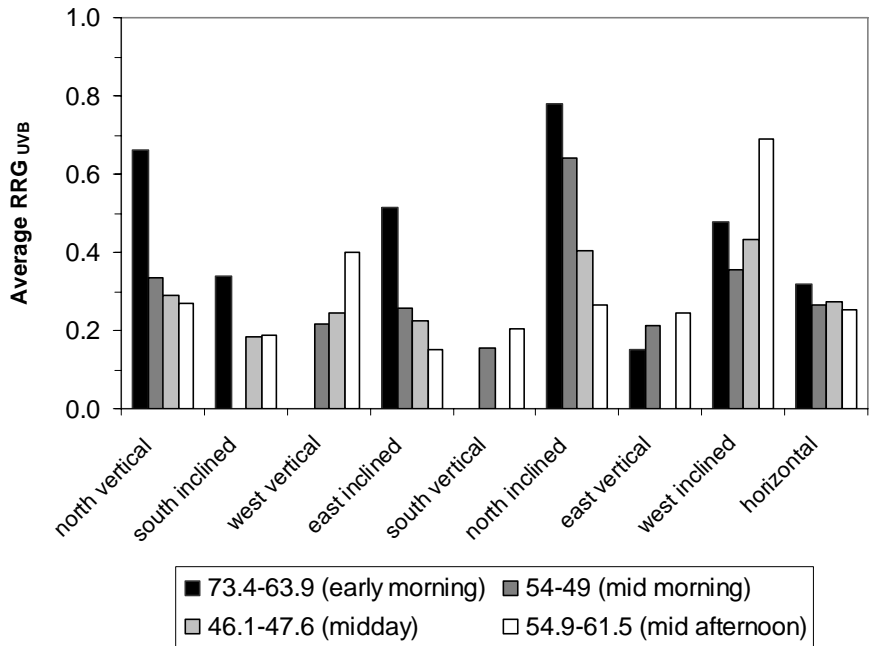
Figure 5 – Average RRG$_{UVB}$ (from 300 nm to 320 nm) albedo for Zincalume surfaces at various orientations, positions and SZA.

Table 1 – Comparison of average RRG$_{UVB}$ radiation over all metal surface types and all SZAs.

Metal Type	Average RRG $_{UVB}$(300 nm – 320 nm)			
	Overall	*Vertical*	*Horizontal*	*Inclined*
Zincalume Trimclad	0.32	0.28	0.28	0.39
Zincalume Corrugated	0.31	0.29	0.28	0.35
Beige Trimclad	0.17	0.15	0.13	0.16
Cream Trimclad	0.27	0.28	0.19	0.25
Cream Corrugated	0.17	0.20	0.11	0.16
Blue Trimclad	0.11	0.12	0.06	0.07
Insultec Trimclad	0.19	0.21	0.14	0.17
Black Trimclad	0.10	0.14	0.04	0.06
Red Trimclad	0.11	0.14	0.04	0.07
Pale green Trimclad	0.12	0.15	0.06	0.07