

# Measurements of UV radiation on rotating vertical plane at the ALOMAR Observatory (69° N, 16° E), Norway, June 2007

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**Abstract.** Erythemal weighted UV and total UV-A irradiance measured at the ALOMAR (Arctic Lidar Observatory for Middle Atmosphere Research; 69° N, 16° E) in June 2007 by two Kipp & Zonen UV broadband meters type, UV-S-EA-T, are examined. One unit is mounted on rotating vertical plane and the other is permanently fixed horizontally. The UV broadband meters measure simultaneously to compare UV irradiances on vertical and horizontal planes. The entire range of such relative exposure variations during clear-sky and overcast conditions over ALOMAR in the period March–June 2007 is examined using STAR and Radonic1 model (developed at the Meteorological Institute, University of Munich) for various action spectra: erythema, UV-A, and vitamin D<sub>3</sub>. The model and observations support that the daily means of relative exposures are quite stable, i.e., vary within the range 0.4–0.6 with the mean around 0.5 when the averaged intra-day, day-to-day, and seasonal changes of the relative erythemal exposures are considered. It seems that multiplication of the daily mean dose from a broadband meter placed horizontally by the factor of 0.5 gives reasonable estimation of the daily mean exposure on a vertically oriented receiver randomly oriented towards the Sun. The model studies during clear-sky conditions show that the extreme value and daily variability of relative exposure are the highest for UV-A, next for erythemal UV, then for vitamin D<sub>3</sub> weighed UV irradiance. The minima of relative exposure (~0.20–0.30) are almost the same for all weighting functions. The comparison of model simulations and measurements suggests that specific cloud configuration could lead to significant enhancement of UV exposure of rotating receiver.

## 1 Introduction

The ozone depletion in the atmosphere over mid and high latitude regions of the globe during the last two-three decades appears as one of the most important ecological threats. The inverse relation of column ozone amount (total ozone) with solar UV-B reaching the Earth's surface triggered many studies of the ozone and surface UV variability. It also led to establishing the ozone and UV global observing network. The UV monitoring is of a special importance because of recognized wide adverse effects of excessive doses on the human beings (e.g. sunburn, snow blindness, non-melanoma skin cancer, cataracts, suppression of immune system etc.). However, there are relatively few good effects of UV radiation penetrating the human body. It is well known that exposure to small amounts of UV-B radiation is essential for synthesizing vitamin D<sub>3</sub> in the skin. It is estimated that approximately 90–95% of the human intake of vitamin D<sub>3</sub> comes from the solar exposure, Holick (2004). Epidemiological data convince that the vitamin D<sub>3</sub> deficit is correlated to breast cancer, prostate cancer, multiple sclerosis, diabetes, osteoporosis, rickets in children, etc., Holick (2004).

The UV irradiance is measured routinely at many places all over the world using broadband instruments and/or spectral radiometers. For public information only UV radiation, which is weighted by the erythemal action spectrum defined by McKinlay and Diffey (1987), is provided in terms of the so-called UV index (WMO, 1994) being integral of biologically weighted UV irradiance measured (or derived from a model) on a horizontal surface. However, such standard does not take into account highly variable orientation of the human body to solar radiation. Parts of human body may be horizontal (e.g., arm), tilted (face), vertical (ears), and facing the ground (chin). Thus investigations of UV effects on



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**Fig. 1.** The measuring system, movable vertically placed and horizontally fixed Kipp & Zonen dual band biometers, at site of ALOMAR Observatory.

the human being need an approach that allows to calculate (or measure) weighted UV irradiance on arbitrarily oriented surfaces.

All routinely measured and modeled weighted UV values were reported for horizontal surfaces that assumed also weighting according to the cosine of solar zenith angle (SZA). Measurements of irradiance on tilted surfaces were carried out for only few locations during short-period campaigns (Schauberger 1990, 1992; McKenzie et al., 1997; Wester and Josefsson, 1997; Parisi and Kimlin, 1999; Webb et al., 1999; and Oppenrieder et al., 2004). To have more comprehensive description of biological UV-effects on arbitrarily oriented surfaces, a numerical model was developed at the Meteorological Institute, University of Munich, Mech and Koepke (2004). The model was validated by comparing the results with earlier measurements by Schauburger (1990), Webb et al. (1999), and Oppenrieder et al. (2004). Koepke and Mech (2005) used the model to examine variability of erythemal weighted solar UV with atmospheric and ground properties.

An alternative approach of examination of UV exposure on the human body was application of the polysulphone (PS) film badges placed on manikin in an upright position, e.g., Kimlin and Schallhorn (2004), Downs and Parisi (2007). PS

**Table 1.** Daily means and their standard deviations (in the parentheses) from auxiliary measurements at the ALOMAR observatory in the period 1–14 June 2007. The configuration of the moving biometer for selected days is coded as follows: H – horizontal position, VS – fixed vertical position towards South during the whole day, VR – random rotation.

Day June	Code of UV Observations	Cloud Optical Depth	Aeros. Optical Depth	Total Ozone
1	H	0.0 (0.4)	0.15	324 (0.1)
2	VR	0.1 (0.4)	0.05	307 (0.7)
3	VS	6.3 (5.0)	–	309 (0.9)
4	VR	2.3 (4.9)	0.08	319 (0.3)
5	VR	49.4 (10.9)	–	320 (0.3)
6	VR	5.1 (5.4)	0.08	320 (0.3)
7	VR	10.0 (3.6)	–	330 (1.2)
8	VR	7.1 (4.6)	–	319 (0.7)
9	VR	26.9 (16.9)	–	338 (0.8)
10	VR	12.5 (14.7)	0.98	347 (2.2)
11	VR	82.3 (36.2)	–	382 (3.3)
12	VR	11.3 (14.1)	0.17	406 (1.9)
13	VR	5.4 (8.6)	0.14	390 (0.8)
14	VR	1.0 (3.1)	0.19	375 (0.5)

film responses to UV radiation similarly to the human skin. Changes in its absorbency at 330 nm were calibrated to the erythemally weighted doses. Data from selected anatomical locations were usually normalized to corresponding exposure for ambient horizontal plane using the approximation of Diefey (1989).

The main objective of this paper is the examination of correspondence between weighted irradiances measured on vertically oriented receiver (being a crude approximation of human face randomly oriented towards the Sun) and those on horizontal receiver. Results of the measurement carried out at the ALOMAR observatory (69° N, 16° E, 390 a.s.l.) in the period 1–14 June 2007 are analyzed to find relation between UV irradiances simultaneously measured by horizontally and vertically oriented biometers (Sect. 2). Section 3 contains the results of simulations of biologically weighted UV irradiances on inclined surfaces under clear-sky and overcast conditions at the ALOMAR observatory in the period 1 March 1–30 June 2007 with special emphasis on the period 1–14 June 2007. Conclusions are presented in Sect. 4.

## 2 Measurements

### 2.1 Biometer and calibration

The UV measurements at the ALOMAR observatory, located near Andenes (Norway), are carried by two Kipp & Zonen (K&Z) dual band biometers, UV-AE-T, in the period 1–14 June 2007. The biometer has a broad spectral response optimized for measurements of erythemal and UV-A part of UV irradiance. It measures the irradiance in two spectral bands

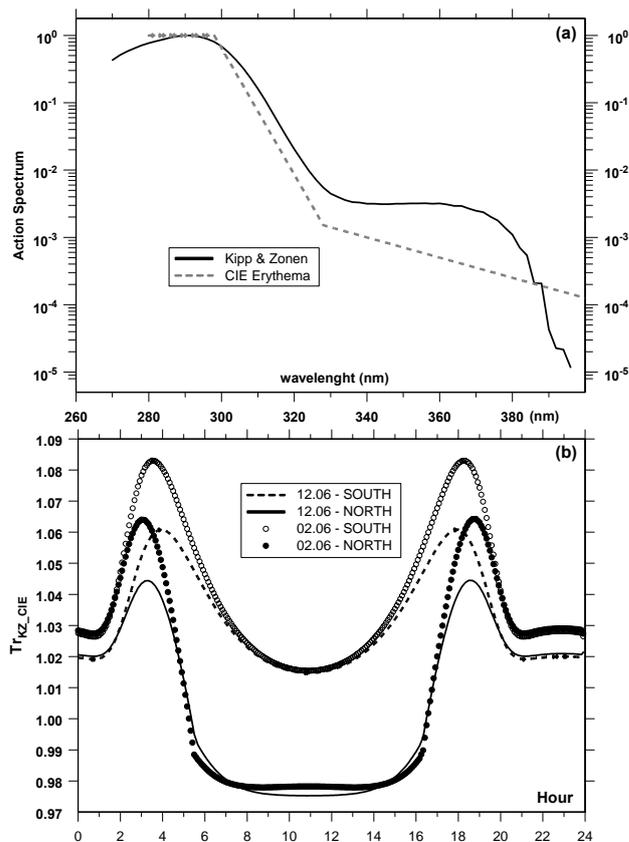
with a single sensor providing separate output for the erythemally weighted irradiance and integrated UV-A irradiance with two separate analog voltage output for each band. The K&Z biometer is temperature stabilized at 25°C. The nominal accuracy of the measured daily sum is expected at best 5%.

Figure 1 shows the measuring setup. The rotor system allows to move a vertical plate on which one K&Z biometer is installed. The other unit is permanently fixed horizontally to provide a reference irradiance used for normalization of the vertical receiver output. The weighted UV irradiances are collected for 8 prescribed azimuth angles  $\phi_P=0^\circ$  (the normal to the plate is towards North),  $45^\circ$ ,  $90^\circ$  (East),  $135^\circ$ ,  $180^\circ$  (South),  $225^\circ$ ,  $270^\circ$  (West), and  $315^\circ$ . The vertical plane is moved forward in  $45^\circ$  steps starting from  $\phi_P=0^\circ$  and ending at  $\phi_P=315^\circ$ . For each position there are 3 measurements with 1-min interval. Clockwise turning to the next position takes  $\sim 30$  s. After the measurement at  $\phi_P=315^\circ$ , the vertical biometer starts turning back to the initial position,  $\phi_P=0^\circ$ , which takes  $\sim 6$  min. During the back rotation 6 samplings are done at random azimuths. The horizon line for the observing site is obscured on West/North–North directions by the laboratory facilities and mountain (see Fig. 1). The measurements between 19–20 h of local time are excluded because of the building shadowing. Moreover, some measurements especially for the sector West/North–North–East/North are not examined because of a weak instrument signal caused by low solar elevations  $<5\%$  or dense clouds.

The results (daily means) of auxiliary measurements by GUV511 (total ozone, cloud optical depth- COD), CIMEL and MODIS sunphotometer (aerosols optical depth-AOD) are shown in Table 1 for the period 1–14 June. MODIS AOD observations are only for 10 June. Moreover, a configuration of the instruments' setup is also added. Two biometers are placed horizontally on 1 June. The vertical biometer is fixed in position towards South on 3 June. COD and its standard deviation let us guess the cloud conditions of the selected days. Days 1 and 2 June are almost cloudless. Days 5, 7, 9, and 11 June are probably fully overcast with especially dense clouds on 5 and 11 July. Thin clouds appear throughout 3, 4, 6, 13, and 14 June. These conditions are also supported by the availability of AOD data.

The horizontal biometer has been compared with that previously calibrated at the Davos observatory during their simultaneous measurements at the Central Geophysical Observatory of the Institute of Geophysics, Polish Academy of Sciences, Belsk ( $52^\circ$  N,  $21^\circ$  E) Poland, in September 2007. A ratio between output of two K&Z instruments, which is assumed to be a function of SZA, has been calculated and used for the correction of output by the horizontal biometer.

The instrument mounted on the rotating plate has been calibrated at the ultraviolet calibration centre in Davos, Switzerland, in August 2006 (Hülse and Gröbner, 2007). The biometer raw signal in Volt,  $U_H$ , when kept in its standard horizontal position, is converted to the erythemal irradiance



**Fig. 2.** CIE erythema action spectrum (dotted line) and the relative spectral response of Kipp & Zonen biometer (full line) – (a), daily course of the KZ-CIE conversion factor for the vertical biometer facing South or North under clear-sky conditions over the ALOMAR observatory on 2 June (open circle – South, full circle – North) and on 12 June (dotted line – South, full line – North) – (b).

on horizontal surface in  $\text{Wm}^{-2}$ ,  $E_{\text{CIE}}^H$ , using the standard calibration procedure (Webb et al., 2006, Seckmeyer et al., 2007):

$$E_{\text{CIE}}^H = (U_H - U_{H,\text{dark}}) \cdot C_H \cdot f_{KZ \rightarrow \text{CIE}}^H(SZA, TO_3) \cdot \text{Coscor}(SZA) \quad (1)$$

where:  $U_{H,\text{dark}}$  is the dark offset in Volt,  $C_H$  is the calibration coefficient,  $f_{KZ \rightarrow \text{CIE}}^H(SZA, TO_3)$  is the model derived calibration matrix depending on SZA and total column ozone,  $TO_3$ , that takes into account the spectral response function of the biometer (see Fig. 2a),  $\text{Coscor}(SZA)$  is the cosine correction function. During the Davos intercomparison it has been found that our K&Z biometer has almost perfect the cosine response in all directions, i.e., it can be assumed that  $\text{Coscor}(SZA) \approx 1$ .

An extension of Eq. (1) to the erythemal irradiance measured on a vertical plane would require a multidimensional calibration matrix,  $f_{KZ \rightarrow \text{CIE}}^V(SZA, TO_3, \phi_S, \phi_P, Alb_L, Alb_{GL}, AOD)$ , where  $\phi_S$  and  $\phi_P$  is the Sun and rotating

**Table 2.** Modeled and observed daily means of ratios between erythemal UV irradiances measured simultaneously by two biometers. One unit is placed horizontally all time, position of the second unit is defined in Table 1. The standard deviations are in the parentheses.

Day June	Observation		Model-Clear Sky		Model-Thick Cloud	
	Temporary values	Daily Doses	Temporary values	Daily Doses	Temporary values	Daily Doses
1	1.00 (0.07)	1.00	–	–		
2	0.49 (0.26)	0.54	0.55 (0.17)	0.53	0.45 (<.01)	0.45
3	0.60 (0.13)	0.70	0.64 (0.14)	0.69	0.45 (<.01)	0.45
4	0.45 (0.19)	0.50	0.53 (0.17)	0.51	0.45 (<.01)	0.45
5	0.45 (0.12)	0.49	0.53 (0.16)	0.51	0.44 (<.01)	0.44
6	0.43 (0.18)	0.51	0.54 (0.17)	0.52	0.45 (<.01)	0.45
7	0.44 (0.11)	0.51	0.53 (0.16)	0.51	0.45 (<.01)	0.45
8	0.44 (0.16)	0.50	0.53 (0.16)	0.51	0.45 (<.01)	0.45
9	0.45 (0.11)	0.49	0.53 (0.16)	0.51	0.45 (<.01)	0.45
10	0.43 (0.17)	0.48	0.48 (0.09)	0.45	0.43 (<.01)	0.43
11	0.37 (0.08)	0.45	0.53 (0.17)	0.51	0.45 (<.01)	0.45
12	0.48 (0.24)	0.51	0.53 (0.16)	0.51	0.45 (<.01)	0.45
13	0.50 (0.28)	0.51	0.53 (0.17)	0.51	0.44 (<.01)	0.44
14	0.48 (0.25)	0.52	0.52 (0.16)	0.51	0.45 (<.01)	0.45

plane azimuth, respectively,  $Alb_L$  and  $Alb_G$  are local and large scale albedo, respectively,  $AOD$  is aerosol optical depth. Such calculations for numerous combinations of the function's arguments would be a time consuming and challenging task. Instead, we propose a model calculation of the  $KZ \rightarrow CIE$  conversion factor,  $Tr_{KZ \rightarrow CIE}$ , to transform the ratio between irradiances measured by the vertical and horizontal biometers to the same ratio but for the erythemal irradiances:

$$Tr_{KZ \rightarrow CIE} = E_{CIE}^V / E_{CIE}^H \cdot (E_{KZ}^V / E_{KZ}^H)^{-1} \quad (2)$$

where:  $E_{CIE}^V$  and  $E_{CIE}^H$  are the model calculated erythemally weighted irradiances on vertical and horizontal UV units with the CIE spectral sensitivity,  $E_{KZ}^V$  and  $E_{KZ}^H$  are the modelled UV irradiances weighted by the KZ spectral sensitivity.  $Tr_{KZ \rightarrow CIE}$  is obtained from radiative model simulations (for details of the radiative model see Sec.3) using the whole period of the observations over ALOMAR with a 10-min time step. Calculations are for 8 positions of the vertical receiver,  $\phi_P = 0^\circ, 45^\circ, 90^\circ, 135^\circ, 180^\circ, 225^\circ, 270^\circ$ , and  $315^\circ$ . Total ozone and aerosol optical depth for each day are from the auxiliary measurements (Table 1). Large scale albedo is taken from the climatological values derived for the site from satellite measurements, Tanskanen (2004). Local albedo is taken for a concrete surface as the instruments are located on a big terrace made of this material.  $Tr_{KZ \rightarrow CIE}$  for selected position of the vertical unit,  $\phi_{P,obs}$ , and time,  $t_{obs}$ , is calculated using the bilinear interpolation between the closest model values:  $Tr_{KZ \rightarrow CIE}(t_1, \phi_{P1})$ ,  $Tr_{KZ \rightarrow CIE}(t_1, \phi_{P2})$ ,  $Tr_{KZ \rightarrow CIE}(t_2, \phi_{P1})$ , and  $Tr_{KZ \rightarrow CIE}(t_2, \phi_{P2})$ , where  $t_1 < t_{obs} < t_2$ ,  $t_2 = t_1 + 10\text{-min}$ ,  $\phi_{P1} < \phi_{P,obs} < \phi_{P2}$ ,  $\phi_{P2} - \phi_{P1} = 45^\circ$ . Examples of the daily courses  $Tr_{KZ \rightarrow CIE}$  for two selected days with the smallest (307 DU, 2 June) and highest total ozone (406 DU, 12 June)

are shown in Fig. 2b. The ratio between the erythemal irradiances measured by the vertical and horizontal units,  $Ratio_{VH,CIE}$ , is estimated as follows:

$$Ratio_{VH,CIE} = Tr_{KZ \rightarrow CIE} \cdot Ratio_{VH,KZ} \quad (3)$$

where  $Ratio_{VH,KZ}$  is the ratio derived from simultaneous measurements by the vertical and horizontal KZ biometers:

$$Ratio_{VH,KZ} = C_V / C_H (U_V - U_{dark,V}) / (U_H - U_{dark,H}) \quad (4)$$

where  $U_V$  and  $U_H$  is raw signal from the vertical and horizontal unit, respectively, the ratio  $C_V / C_H$  between instrumental calibration coefficients for the vertical and horizontal KZs is obtained from simultaneous observations on 1 June 2007. The value was corroborated by the similar measurements at Belsk (Poland) in September 2007 when both K&Z biometers were placed horizontally for much longer time.  $Tr_{KZ \rightarrow CIE}$  values are calculated separately for clear-sky conditions and a homogeneous plane parallel thick cloud. The switch between two cases for  $Tr_{KZ \rightarrow CIE}$  in Eq. (3) is arbitrarily taken when the Sun is obscured by a dense cloud, i.e., ALOMAR GUV data gave the atmospheric transparency lower than 90% of expected clear-sky value.

K&Z biometer provides also integrated UV irradiance over the wavelength range of 320–400 nm. For the calculation of UV-A irradiance in absolute unit ( $W/m^2$ ) we use the calibration constant provided by the manufacturer. The quality of the UV-A measurements by our biometer needs further check with well calibrated spectrophotometer. Thus, the results of UV-A measurements in absolute units should be treated with caution. However, an absolute calibration of the instrument is not a key point here because we are mostly focused on comparison between readings of the horizontal

**Table 3.** The same as Table 2 but for the integrated UV-A radiation.

Day June	Observation		Model-Clear Sky		Model-Thick Cloud	
	Temporary values	Daily doses	Temporary values	Daily doses	Temporary values	Daily Doses
1	1.01 (0.02)	1.00	–	–		
2	0.55 (0.29)	0.55	0.62 (0.34)	0.58	0.45 (<.01)	0.45
3	0.62 (0.13)	0.68	0.65 (0.20)	0.72	0.45 (<.01)	0.45
4	0.51 (0.19)	0.51	0.60 (0.31)	0.56	0.44 (<.01)	0.44
5	0.46 (0.06)	0.47	0.60 (0.33)	0.56	0.45 (<.01)	0.44
6	0.51 (0.18)	0.51	0.61 (0.33)	0.57	0.45 (<.01)	0.45
7	0.50 (0.08)	0.50	0.59 (0.30)	0.56	0.45 (<.01)	0.45
8	0.50 (0.14)	0.51	0.59 (0.30)	0.56	0.45 (<.01)	0.45
9	0.46 (0.08)	0.48	0.59 (0.30)	0.56	0.45 (<.01)	0.45
10	0.48 (0.15)	0.48	0.48 (0.13)	0.47	0.43 (<.01)	0.43
11	0.42 (0.07)	0.43	0.59 (0.31)	0.56	0.45 (<.01)	0.45
12	0.51 (0.20)	0.52	0.59 (0.30)	0.55	0.45 (<.01)	0.45
13	0.54 (0.24)	0.52	0.59 (0.30)	0.56	0.45 (<.01)	0.45
14	0.55 (0.26)	0.53	0.58 (0.29)	0.55	0.44 (<.01)	0.44

and vertical units. The ratio between UV-A output of our biometers has been calculated in dependence of SZA during the intercomparison of K&Z biometers at the Belsk observatory after the ALOMAR campaign. This calibration ratio has been applied to the ALOMAR UV-A data.

## 2.2 Vertical versus horizontal biometer data

Table 2 shows daily means and standard deviations of the temporary ratios between UV irradiances measured by two biometers, ratios between their daily doses, and pertaining ratios from the model simulations (discussed further in Sect. 3) in the period 1–14 June 2007. The measured ratios are close to 1 on 1 June when both instruments are placed horizontally. Moreover, the mean difference between daily maxima of erythemal irradiances at horizontal surface taken by K&Z instrument and GUV511 meter routinely collecting UV data at the ALOMAR observatory is  $\sim 6\% \pm 5\%$  over the whole period of the observations. The deviation between high quality measurements with various erythemally weighted broadband instruments was in the range of 8% (Leszczynski et al., 1995). Thus, it seems that our horizontal unit provides valuable data in spite of lack of its own calibration matrix. However, the comparison of the UV irradiances by the vertical and horizontal units should be treated with caution because an assumption that the instruments are identical is not supported by laboratory investigations of their spectral characteristics (e.g. action spectrum, cosine error also depending on azimuth). Model calculations will provide a kind of validation of the measured output ratios.

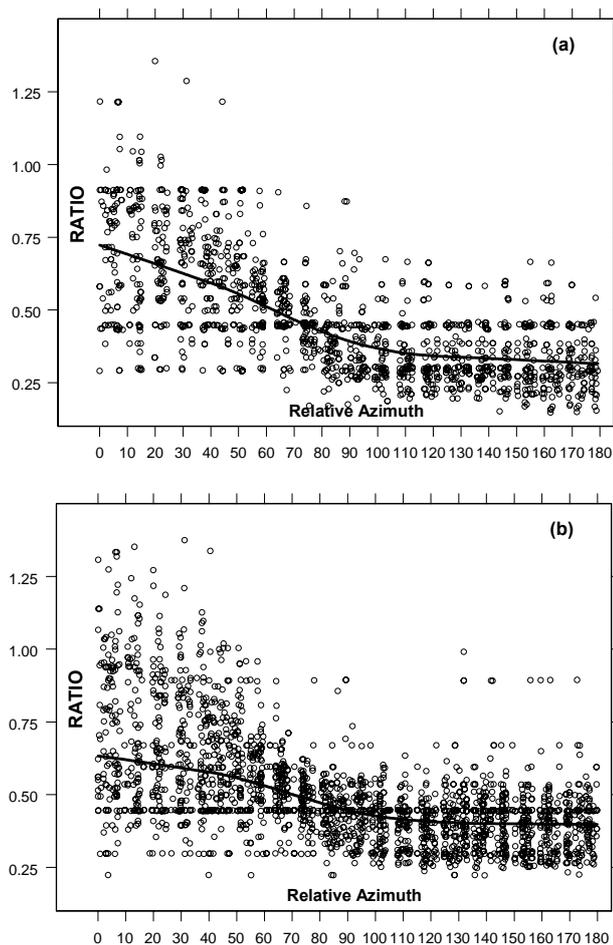
Table 3 shows results of the instrument and model comparisons for the integrated UV-A irradiance. There is perfect agreements on 1 June when both instruments are placed horizontally. We have no additional arguments for the in-

struments' identity and reliability of the data simultaneously taken by the receivers. Only model calculations provide some insight into the reliability of the calculated ratios.

Figure 3 presents a dependence of the relative exposure (temporary ratio between output of the vertical and horizontal receivers) on relative azimuth,  $\phi_{\text{rel}}$ , i.e., an angle between azimuth of the normal to the instrument diffuser and the Sun azimuth. All temporary measurements for the period 2–14 June 2007 are shown. Number of UV-A data points is larger because of weak instrument output (Volt) for the UV-B range for high SZA ( $>80^\circ$ ) and dense clouds. The uncertainty of the logger system used precludes a precise calculation of the relative exposure in such cases. The overall mean calculated from all temporary ratios shown in Fig. 3 is  $0.45 \pm 0.03$  and  $0.50 \pm 0.04$  for the erythemal UV and integrated UV-A irradiation, respectively.

A case with the relative azimuth larger than  $90^\circ$  corresponds to a shadowing of vertical instrument. The ratios are less variable and smaller ( $<0.50$ ) for  $\phi_{\text{rel}} > 90^\circ$ . For overcast conditions with dense clouds (opaque the Sun disk), the relative exposure is close to values found when the rotating plane is in a shadow. The variability of irradiance measured by the vertical unit is nearly independent of its azimuth because the UV radiation consists of diffuse radiation being close to homogeneous during heavy overcast conditions. Similar findings concerning variability of the erythemal UV over inclined surfaces were discussed by Oppenrieder et al. (2004).

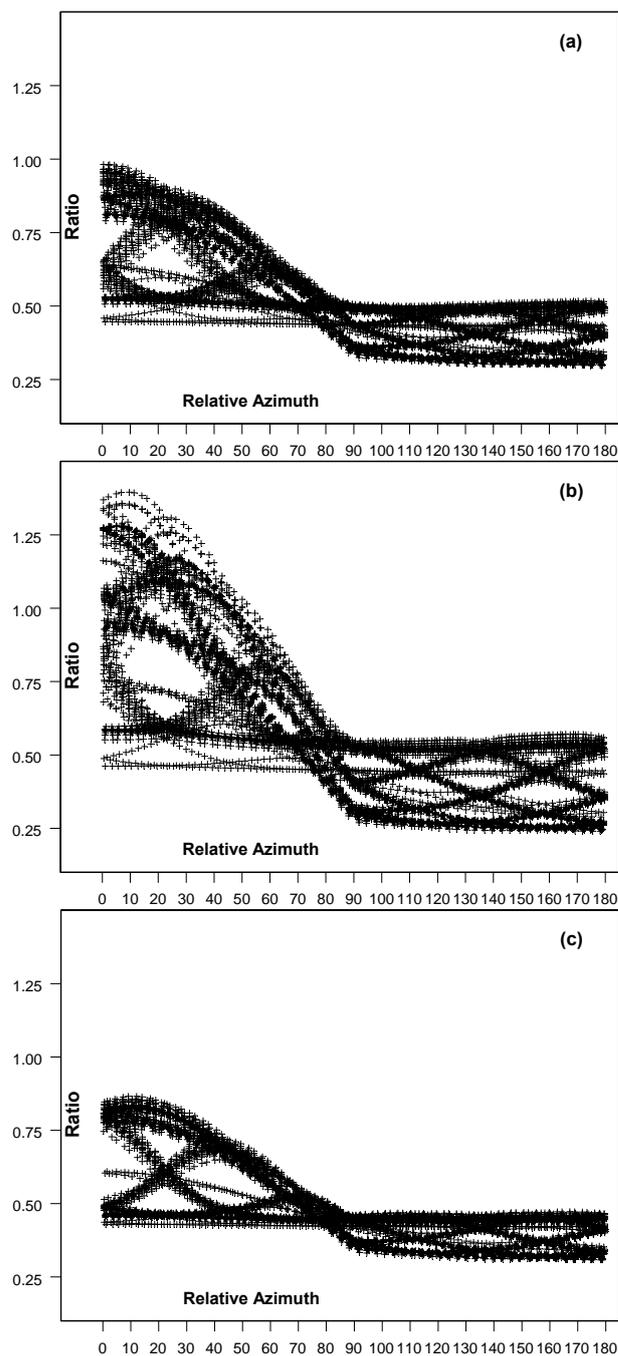
The larger relative exposures are found when the vertical instrument is facing sun line. There are substantial variations of the relative exposures for selected relative azimuth, especially when  $\phi_{\text{rel}} < 90^\circ$ . It is probably caused by variability of direct sunlight contribution to total illumination of the vertical receiver due to the cosine weighting and cloud effects.



**Fig. 3.** The ratio between UV irradiances measured at the ALOMAR observatory by rotating vertical biometer and horizontally placed biometer as a function of relative azimuth for the period 2–14 June 2007: erythemally weighted irradiances – (a), integrated UV-A irradiances – (b).

Some of these effects will be illustrated in Sect. 3 where model results are shown. It is worth noting that sometimes relative exposures  $>1$  appear. Such enhancements are more frequent for UV-A measurements. It cannot be excluded that a specific cloud configuration yielding incoming of additional portion of sky radiance on the vertical plane due to multireflections of the sun radiation by clouds is responsible for such enhancements. This problem will be discussed in Sect. 3 where results of the model calculations are compared with the observed data.

The comparison of the daily mean values of relative exposures shown in Table 2 and Table 3 yields that the ratio is higher and more variable for clearer days. However, the measurements show that day-to-day variations of the ratio between daily doses by the vertical and horizontal units are quite small, i.e., within the range 0.45–0.54 and 0.43–0.55 for erythemal UV and integrated UV-A irradiation, respec-



**Fig. 4.** The same as Fig. 3 but the ratios are from the model simulations for clear-sky conditions at the ALOMAR observatory in the period 2–14 June 2007: erythemally weighted irradiances – (a), integrated UV-A irradiances – (b), vit.  $D_3$  weighted irradiances – (c).

tively. The overall mean calculated from all daily ratios is  $0.50 \pm 0.02$  and  $0.51 \pm 0.03$ , for erythemal UV and integrated UV-A irradiation, respectively. Special non random configuration of the biometers on 3 June when the vertical unit was

facing South throughout the whole day, causes an increase of the ratios (above 0.6) and lowering of standard deviations. It is also supported by the model calculations for that day suggesting reliability of the measured relative exposures.

### 3 Model results

The irradiance on an arbitrarily oriented plane is modeled by integration of radiances weighted according to the cosine of the angle between direction of every incoming radiance and the plane normal. This is done by Radonic1 model developed by Mech and Koepke (2004). The radiances are modeled with STAR, System for Transfer of Atmospheric Radiation (Ruggaber et al., 1994; Schwander et al., 2000), which is known to be of high quality (Koepke et al., 1998). The quality of the model irradiances on vertical surfaces has been corroborated by results of automatic measuring system, Angle SCAanning RAdiometer for determination of erythemally weighted irradiance on Tilted Surfaces (ASCARATIS), that was developed by the Meteorological Institute and the Institute of Outpatient Clinic for Occupational and Environmental Medicine in Munich (Oppenrieder et al., 2004; Mech and Koepke, 2004).

The ratio between irradiation on vertical and horizontal surfaces is calculated separately for clear-sky and overcast conditions in the period 2–14 June with a 10-minute time step. Selected combinations of the plane azimuths correspond to the rotor azimuth schedule. The model input consists of total ozone from GUV511 observations. AODs at 500 nm are from the CIMEL sunphotometer measurements. MODIS AOD observation on 10 June is taken into account as it was no CIMEL observations. Constant AOD value of 0.13, i.e., the mean AOD for the whole campaign, is used for cases with no satellite or ground observations of aerosols. Single scattering albedo and asymmetry function in the lower troposphere are assumed as those for the continental averaged aerosols. Global albedo value in UV range of 0.05 represents climatological mean at 360 nm for the site derived from Tanakanen (2004) albedo data base. Local albedo value is for a concrete surface as the instruments are located on a big plane roof made of this material (see Fig. 1). Climatological values (Arctic summer) for the pressure levels, temperature, humidity, and ozone profile are selected. Erythemal action spectrum (McKinlay and Diffey, 1987), vit. D<sub>3</sub> action spectrum (CIE, 2006), and integrated UV-A irradiance (equal 1 for the 320–400 nm range otherwise equal 0) are considered. Cloud assumed for overcast simulations represents homogeneous plane parallel cloud that extends between 1–1.5 km with the liquid water content of 0.3 g/m<sup>3</sup>.

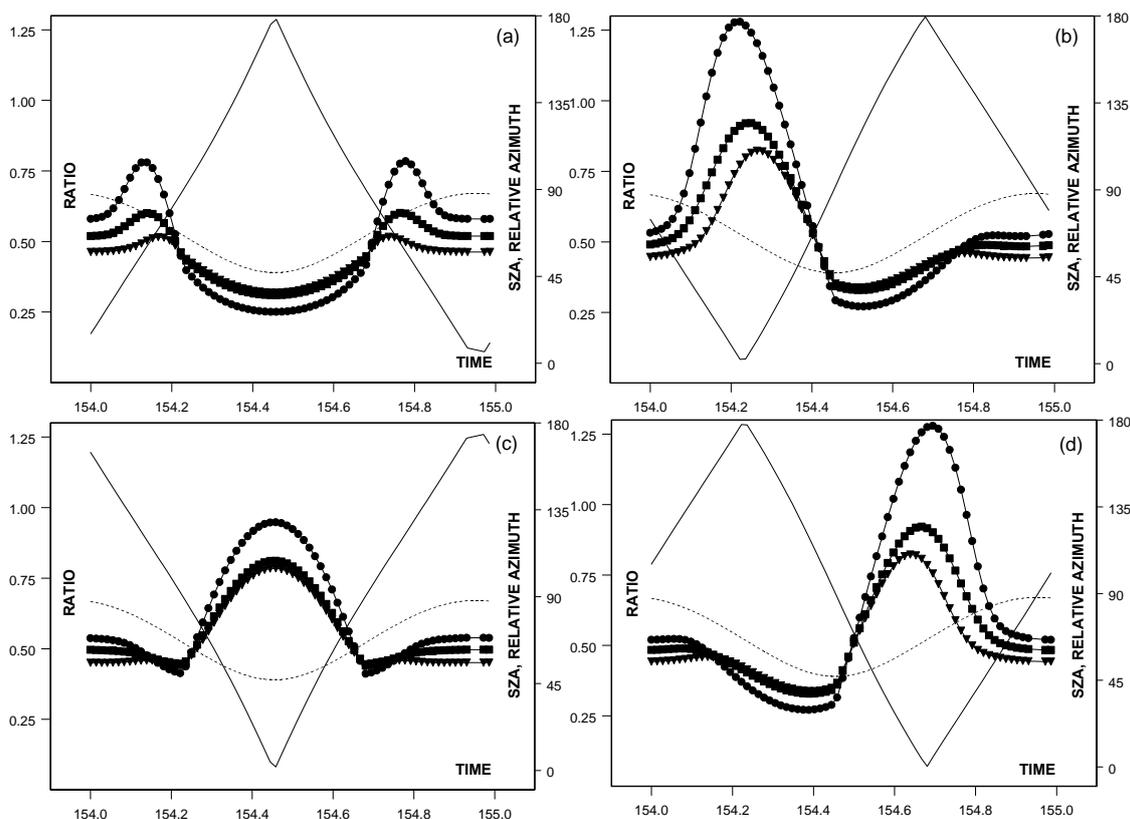
The daily mean ratio of temporary relative exposures and ratio between daily doses from the model and ALOMAR observations are shown in Table 2 and Table 3. The clear-sky ratios are larger with higher intraday variability than those obtained under uniform heavy cloud. It is worth mention-

ing that the differences between both cases are not large. The span of model relative exposures derived from the daily doses is 0.43–0.53 and 0.43–0.58 for the erythemal UV and integrated UV-A, respectively. The measured values shown in Table 2 and Table 3 are somewhere between the modeled values found for clear-sky and overcast conditions. The daily mean of the ratio on 11 June is lower than pertaining overcast estimate probably because the model setup is not representative for that day due to heavy clouds extending up to ground. The observed ratios for 3 June are the largest and correspond to the specific biometer's configuration on that day, i.e., the vertical biometer facing South during the whole day. The observed enhancement of the ratio on 3 June is corroborated by the model results. High aerosols loading of the atmosphere significantly affects the relative exposure. AOD of 0.98 is used for the model calculation on 10 June providing smaller value of relative exposure under clear-sky and overcast conditions. It seems that the factor of 0.5 could be used as a good approximation of the averaged relative exposures under all-sky conditions during the ALOMAR campaign. The model results and observations for random orientation of the vertical receiver show that almost all daily means of relative temporary exposures are in the range  $0.5 \pm 0.1$ . The same factor also pertains the ratio between daily sums by the vertical and horizontal biometers.

Figure 4 illustrates the modeled erythema, vit. D<sub>3</sub>, and UV-A weighted irradiances on vertical surface divided by the irradiances calculated on horizontal surface as a function of relative azimuth under clear sky conditions. All modelled temporary ratios in the period 2–14 June are included. Input parameters come mostly from auxiliary measurements as it was mentioned earlier in the text. The highest maxima and variability of relative exposures (calculated as a distance between maximum and minimum) are for UV-A, next for erythemal UV, then for vit. D<sub>3</sub> weighted irradiances. The minima ( $\sim 0.20$ – $0.30$ ) are almost the same for all examined action spectra.

The relative exposures  $> 1$  are found during clear-sky conditions only for the integrated UV-A irradiances. The ozone absorption causes a cut off of the direct Sun component of UV-B radiation being larger for higher SZAs. Whereas, the direct sunlight within UV-A range is still present and it contributes stronger to radiation measured by the vertical biometer (the cosine effects) because for high SZA there is possibility that this receiver is looking directly at the Sun disk but the horizontal unit practically does not see the Sun line (Figs. 5b and 5d). A comparison of Fig. 4 and Fig. 3 suggests that the relative exposures above 1 obtained from the measurements of the erythemally weighted UV irradiance are not possible under clear-sky conditions, so the solar radiation enhancements due to cloud reflections are possible source of the observed extreme ratios.

Figure 5 illustrates intra-day variations of the clear-sky relative exposures on 3 June for fixed 4 positions of a vertical receiver: North, East, South, or West. It is seen that intra-day



**Fig. 5.** The modelled ratio between weighted UV irradiances obtained by vertical biometer and horizontally placed biometer for fixed azimuth of the vertical one on 3 June 2007 for various action spectra (circles- integrated UV-A, squares- erythemal weighting, triangles- vit. D<sub>3</sub> weighting): North- (a), East- (b), South- (c), West- (d). Solid and dotted curve show daily pattern of the relative azimuth and SZA, respectively.

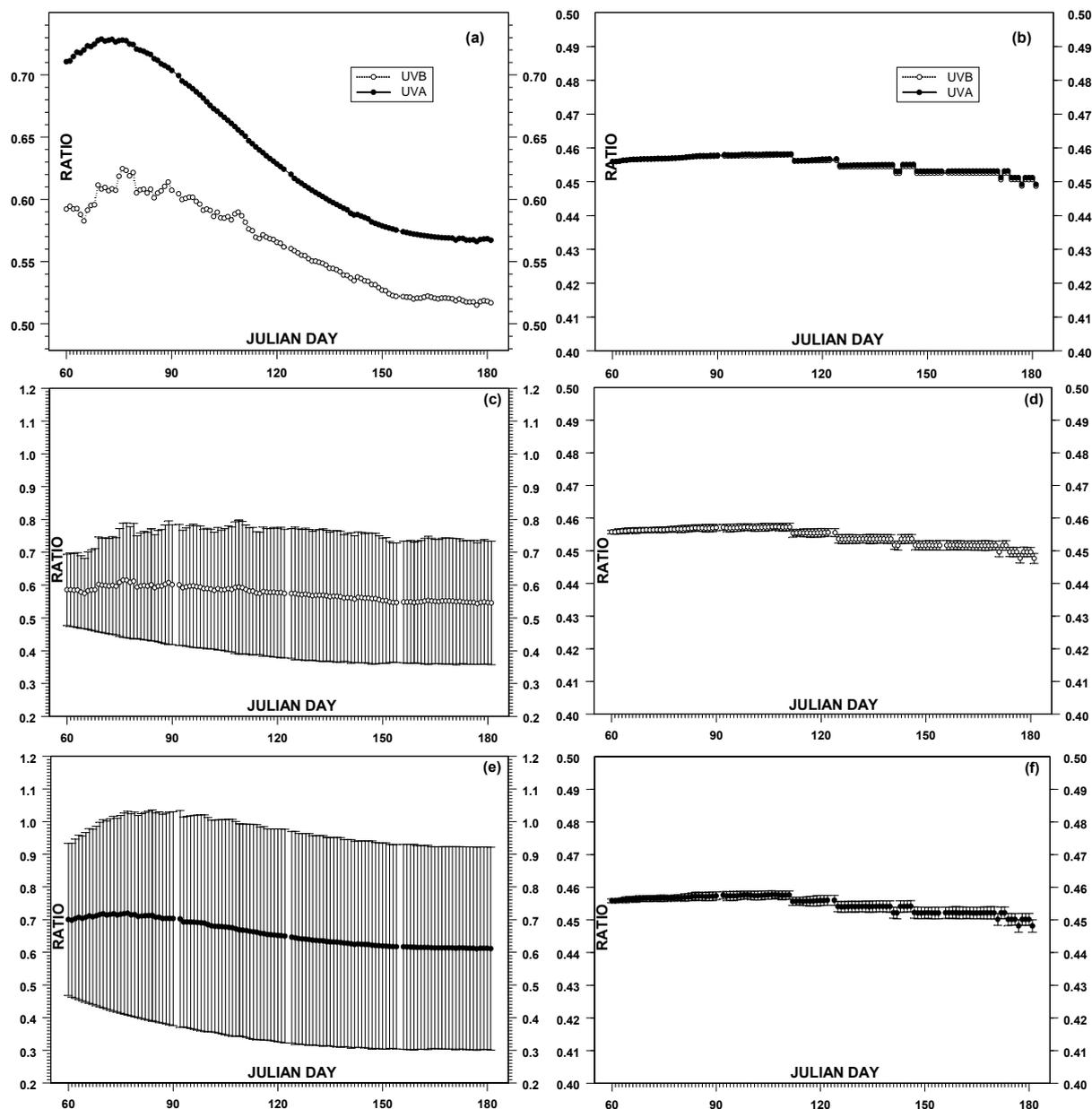
fluctuations of the relative exposures are a compound function of the Sun elevation, sun/instrument orientation, and action spectra. The same calculations with an opaque cloud give uniform pattern of relative exposures  $\sim 0.45$  independent on SZA, relative azimuth, and total ozone.

A question arises if the daily means of relative exposures change over longer (seasonal) time scales. We repeat radiative model simulations for the period 1 March 1–30 June 2007 using reliable input: total ozone data are from the site overpasses by Ozone Monitoring Instrument (on board of the AURA spacecraft), large scale albedo from the site climatology derived from Tanskanen (2004) albedo data base, local albedo (assuming snow albedo until the end of April and albedo for a concrete surface afterwards), AOD at 550 nm of 0.13 (equal to the mean AOD value during the period 1–14 June), other parameters are fixed to the climatological values (vertical profiles of ozone, temperature, and humidity). For overcast conditions we assume that low level cloud extends between 1–1.5 km with liquid water content of  $0.3 \text{ g/m}^3$ . The erythemal UV and integrated UV-A irradiances on horizontal and vertical surfaces are examined for the same set of the azimuth angles programmed for the rotor motion in the period 1–14 June. The results are shown in Fig. 6.

The maximum of the ratio between daily doses taken by vertical and horizontal biometers is found around mid March, i.e., 0.63 and 0.73 for the erythemal UV and integrated UV-A, respectively. The maximum is less pronounced for the pattern of daily means of temporary relative exposures. Under heavy cloud conditions the relative exposures do not exhibit any seasonal and intraday pattern. It seems that the factor of 0.5 still provides a reasonable estimate of the vertical/horizontal ratio under mixed cloudy conditions throughout a day. The factor should be enlarged of  $\sim 0.1$  in case of integrated UV-A irradiances for clear-sky days in the late winter and early spring.

#### 4 Conclusions

Standard UV irradiance measurements are carried out by broadband instruments (biometers) and spectrophotometers mounted on horizontal surface. At numerous sites biometers have started monitoring of erythemally weighted UV since early 1990s (WMO, 2007). It is possible to weight UV irradiance by any action spectrum using spectral measurements but such instruments are much more expensive, thus less



**Fig. 6.** The ratio between daily sum of UV irradiances by the vertical and horizontal biometers at the ALOMAR site from the model simulations in the period 1 March–30 June 2007: clear-sky –(a), horizontally uniform heavy cloud (b). The daily means  $\pm$  standard deviations of the intra-day ratios between output of both instruments for various action spectra: erythemal UV and clear-sky –(c), erythemal UV and homogeneous heavy cloud - (d), integrated UV-A and clear-sky - (e), integrated UV-A and homogeneous heavy cloud – (f).

frequent in the UV observing network. To estimate more precisely risk of UV overexposure (causing, for example, harmful sunburn) or underexposure (leading to deficit of vit. D<sub>3</sub> in the human body) we need information of weighted UV irradiance on arbitrarily oriented surfaces because of highly variable orientation of the human body relative to solar radiation. There are case studies or short campaign focusing on insolation over various parts of the human body that is inferred from the PS badges attached to manikin (e.g., Downs and

Parisi, 2007) or human beings (e.g., Siani et al., 2007). The monitoring of UV exposures over longer periods and over many sites is complex issue. There is possibility to estimate weighted UV irradiance on inclined surfaces using the radiative transfer model as discussed in previous section. However, the model is based on rather time consuming procedures and required detailed input data that are sometimes unavailable, for example, ozone profile, albedo, aerosol properties, etc. Based on the radiative model simulations and

measurements at the ALOMAR observatory we suggest, as a first approximation, that the daily mean of erythemally weighted and integrated UV-A irradiance on randomly rotating vertical plane is roughly half of that measured on a horizontal surface. Radiative model simulations and observations support that the daily means of relative exposures are quite stable, i.e., vary within the range 0.4–0.6 with the mean around 0.5 when the averaged intra-day, day-to-day, and seasonal changes of the relative erythemal exposure are considered. The factor should be enlarged of  $\sim 0.1$  in case of the integrated UV-A irradiances for clear-sky days in the late winter and early spring.

A question arises if daily sum of weighted irradiance measured by a vertical receiver randomly oriented towards the Sun has something to do with real erythemal exposure of the human face. Recently Downs and Parisi (2007) developed a three dimensional computer model of the human face based on the PS dosimeter measurements on a manikin headform. The headform was placed on a rotating platform (two revolutions every minute) in a vertical position. Averaging relative erythemal exposures measured on selected areas throughout the whole manikin face, which were shown in their Table 2, we estimate that the daily mean of relative erythemal exposure is  $\sim 0.49$ , i.e., close to our estimate. Thus, daily average of erythemal exposure measured on a rotating plane provides reasonable estimate of daily exposure of the human face randomly oriented towards the Sun.

The results presented here are only for a specific site - the northern high latitude. We think that the paper can be treated as a pilot study. Evidently, more efforts are needed to calculate latitudinal/longitudinal differences of relation between output of vertically and horizontally oriented receivers.

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