



1 **Bipolar long-term high temporal resolution broadband**  
2 **measurement system for incoming and outgoing solar UV**  
3 **radiation, and snow UV albedo, at Sodankylä (67°N) and**  
4 **Marambio (64°S)**

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6 Meinander O<sup>1</sup>, Aarva A<sup>1</sup>, Poikonen A<sup>1</sup>, Kontu A<sup>2</sup>, Suokanerva H<sup>2</sup>, Asmi E<sup>1</sup>, Neitola K<sup>1</sup>, Rodriguez  
7 E<sup>1</sup>, Sanchez R<sup>3</sup>, Mei M<sup>3</sup>, de Leeuw G<sup>1,4</sup> and Kyrö E<sup>2</sup>

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9 [1] {Finnish Meteorological Institute, Helsinki, Finland}

10 [2] {Arctic Research, Finnish Meteorological Institute, Sodankylä, Finland}

11 [3] {Servicio Meteorologico National, Marambio, Argentina}

12 [4] {Department of Physics, University of Helsinki, Helsinki, Finland}

13

14 Correspondence to: Outi.Meinander@fmi.fi

15

16 **Abstract**

17 The polar regions of the Earth are characterized with low solar elevation angles, cold temperatures  
18 and large amount of snow and ice. Under the harsh polar conditions, good quality *in situ*  
19 measurements of incoming and outgoing solar radiation, and surface albedo, is a major challenge.  
20 Both in the Arctic and Antarctic, the solar radiation at the wavelengths of ultraviolet (UV) has been  
21 of particular interest due to the polar stratospheric ozone depletion, which increases UV radiation  
22 on the ground (with multiple effects, such as UV-induced DNA-damage). In the presence of light  
23 absorbing impurities (OC/BC/dust) in snow, albedo can be most affected at the wavelengths of UV.  
24 Here we provide, for the first time, the description, comparison and evaluation of our bipolar  
25 measurement design, instrumentation and data system, calibration assessment, as well as  
26 challenges, for measuring incoming and outgoing UV radiation (from which snow albedo is  
27 calculated) at the Sodankylä Arctic Research Centre (67°N) and at the Marambio Antarctic  
28 Research Station (64°S). Both stations are members of the Global Atmosphere Watch GAW



29 programme of the World Meteorological Organization WMO and have personnel available year-  
30 round. The Sodankylä snow UV albedo measurements were started in 2007, as part of the  
31 International Polar Year IPY (2007–2008). The Marambio surface UV albedo measurements, since  
32 February 2013, are part of the Argentinian-Finnish scientific co-operation on meteorological and  
33 atmospheric observations. The paper aims to give a comprehensive insight into our bipolar  
34 measurement system, and to create an understanding needed for a successful scientific utilization of  
35 these data, including satellite and modeling approaches. We also present a literature review of our  
36 previous publications on Sodankylä snow UV albedo data.

37

## 38 **1 Introduction**

39 The polar regions of the Earth are characterized with low solar elevation angles, cold temperatures  
40 and large amount of snow and ice. Detecting changes in polar snow and ice albedo is of critical  
41 importance for monitoring and modeling climate change, atmospheric chemistry, and satellite  
42 applications. Under the harsh polar conditions, continuous good quality *in situ* measurements of  
43 incoming and outgoing solar radiation present a major challenge.

44 The solar radiation reaching the ground surface at wavelengths of ultraviolet (UV) has been of  
45 particular interest in both polar regions ever since the first observations of springtime losses of  
46 ozone over Antarctica (Farman et al. 1985). The stratospheric ozone layer protects the life on Earth  
47 from the Sun's harmful UV radiation by blocking all of the UV-C radiation, and most of the UV-B,  
48 and about half of the UV-A. Also the solar elevation and clouds, air pollution, haze, and the  
49 elevation above sea level affect the amount of UV radiation reaching the ground. The multiple  
50 effects of UV irradiance include, for example, the harmful DNA damage (Sinha and Häder 2002)  
51 and skin cancer, and the positive effects the production of vitamin D in the human skin. When UV  
52 radiation is reflected from snow and ice, it may cause unprotected eyes the painful condition of  
53 snow blindness (UNEP 2002). UV surface albedo is also an essential parameter for various RT  
54 modeling applications, including satellite retrieval algorithms (Arola et al. 2003, Tanskanen and  
55 Manninen 2007). Furthermore, snow albedo can be most affected at the wavelengths of UV in the  
56 presence of light absorbing impurities (Meinander et al. 2013).

57 Here we for the first time describe, compare and evaluate our successful long-term high-temporal  
58 resolution bipolar measurement design, instrumentation and data systems, and calibration  
59 assessment, on incoming and outgoing solar radiation, and snow albedo, at ultraviolet (UV)  
60 wavelengths at the Sodankylä Arctic Station (67°N), and at the Marambio Antarctic Station (64°S).



61 The term “Arctic” is used to refer to north of 60° northern latitude, and “Antarctic” to south of 60°  
62 southern latitude. The purpose of this work is to provide a scientific reference for the Sodankylä and  
63 Marambio measurement systems. The data are planned to be provided in open access data bases, to  
64 allow a wider utilization of the data, e.g., in the WMO Antarctic Ozone Bulletins. Hence, this paper  
65 aims to provide a reference needed by the data users. Although the focus of this paper is not to  
66 publish the existing bipolar data or their scientific analysis (such a paper is at planning stage), we  
67 will give a short review of the existing publications on Sodankylä snow UV albedo data (Meinander  
68 et al. 2008, Meinander et al. 2009, and Meinander et al. 2013). The authors are not aware of any  
69 previous literature review on snow UV albedo, and this is the first time we present a review of our  
70 Sodankylä snow UV albedo results. Also, this is our first paper to consider the Sodankylä incoming  
71 irradiance as an independent data set (instead of albedo). We will also discuss the potential of these  
72 bipolar data for modeling and remote sensing applications.

73

## 74 **2 Materials and methods**

### 75 **2.1 The polar WMO GAW stations of Sodankylä and Marambio**

76 Both the Sodankylä and Marambio stations belong to the Global Atmosphere Watch (GAW)  
77 programme of the World Meteorological Organization (WMO) ([www.wmo.int/gaw](http://www.wmo.int/gaw)). The focal  
78 areas of GAW are aerosols, greenhouse gases, selected reactive gases, ozone, UV radiation, and  
79 precipitation chemistry or atmospheric deposition. Sodankylä is situated in the Finnish Lapland, and  
80 Marambio is an Argentinian Antarctic Base (Fig. 1). We use the same type of broadband UV  
81 instrumentation in Marambio and Sodankylä to allow scientific bipolar comparisons.

#### 82 **2.1.1 Sodankylä Arctic Research Centre**

83 The Arctic snow UV albedo is measured at the Sodankylä Arctic Research Centre of the Finnish  
84 Meteorological Institute (FMI), Finland (67°22'N, 26°39'E, 179 m a.s.l.). The area is north of the  
85 Arctic Circle and belongs to the northern boreal forest zone, with the snow type of taiga. The  
86 seasonal snow cover in Sodankylä lasts in average from 15 October to 14 May (FMI statistics for  
87 1981-2010, [www.fmi.fi](http://www.fmi.fi)). For solar irradiance, Sodankylä is characterized with solar extremes:  
88 nights of the Midnight Sun (no Sun set) from 30 May till 15 July, and Polar Nights (no Sun rise)  
89 from 19 to 25 December ([www.sodankyla.fi](http://www.sodankyla.fi)). Sodankylä is often beneath the middle or the edge of  
90 the stratospheric polar vortex, and in the zone of polar stratospheric ozone depletion.



91 We measure the UV albedo at the FMI Sodankylä Arctic Centre operational albedo field (Fig 2).  
92 The size of the field is 16 m×16 m, and low metal fences protect the operational field to have as  
93 untouched snow surface during snow-time as possible. The snow UV albedo measurements were  
94 started in 2007, as part of the International Polar Year IPY (2007–2008) ORACLE-O3 cluster  
95 project (Ozone layer and UV radiation in a changing climate evaluated during IPY, [http://www.awi-](http://www.awi-potsdam.de/atmo/ORACLE-O3)  
96 [potsdam.de/atmo/ORACLE-O3](http://www.awi-potsdam.de/atmo/ORACLE-O3), Meinander et al., 2008, 2009).

### 97 **2.1.2 Antarctic Marambio Base**

98 The Antarctic UV albedo is measured at the Argentinian Antarctic Marambio Base (64°14'S,  
99 56°37'W, 198 m a.s.l.). The station is located in the ice-free Marambio Island, on the north-east side  
100 of the Antarctic Peninsula. The ecosystem type is Permafrost. The Antarctic region has no  
101 permanent human habitation, but the Marambio Base is manned all-year-round. Marambio is of  
102 great significance to studies related to the Antarctic Ozone Hole because it is on the edge of the  
103 polar vortex. The polar spring arrives in Marambio in September or October, with return of  
104 sunlight. However, the frequency of cloud-free days is small throughout the year, on average only  
105 0-1 from November to February, and the mean frequency of days with snow fall varies between the  
106 maximum 16 days in January to 7 - 8 days in June-September; snowfall is most common from  
107 October to March (SMN statistics for 1971-1990, [www.smn.gov.ar](http://www.smn.gov.ar)). Antarctic Peninsula has  
108 experienced warming at rates several times the global mean (Trenberth et al. 2007).

109 The continuous Antarctic snow UV albedo measurements were started in 2013, as an Argentinian-  
110 Finnish scientific co-operation of FMI and SMN. The measurements were installed to a new  
111 container (Figure 3). In addition to the continuous measurements of the incoming and outgoing  
112 ultraviolet radiation, i.e. snow UV albedo, the container houses a new weather station, and  
113 instruments to measure the optical properties, numbers and chemical composition of aerosol  
114 particles, and the concentrations of carbon dioxide and methane. Due to the extremely windy  
115 conditions in Marambio, the snow cover is sometimes blown away in one place revealing the bare  
116 ground (also under the albedo sensors), while the wind may drift snow in other places. Therefore,  
117 the surface photographs are essentially needed to evaluate the surface condition during the albedo  
118 measurements (snow/no snow). Also, the Antarctic Peninsula differs from most of Antarctica by  
119 having a summer melting season. Summer melt can produce snow-free areas.

### 120 **2.2 Bipolar broadband UV albedo**



121 Snow surface broadband UV albedo in Sodankylä and Marambio is measured bi-hemispherically  
122 using two SL501 (Solar Light Co.) radiometers in both places. This means a maintenance and  
123 calibration need of four SL-501 sensors. For detecting albedo, one sensor is installed to face  
124 upwards, and the other downwards. According to the WMO, the operational meteorological local  
125 albedo is defined to be measured at a standard height of 1–2 m (WMO, 2008, I. 7). This defines the  
126 measurement height of 2 m for Sodankylä and Marambio UV albedo measurement

127 In principle, such UV broadband radiometers have simple operational requirements. Yet, the  
128 relationship between the raw signal and the UV radiation product requires characterization and  
129 calibration procedure for each individual broadband radiometer (Hülsen and Gröbner 2007).

130 The well maintained and calibrated radiometer pairs are selected to represent as similar spectral and  
131 cosine responses as possible, as demonstrated in Fig. 1 of Meinander et al. (2008). The radiometers  
132 measure the incoming irradiance weighted with the action spectrum for ultraviolet induced  
133 erythema (McKinlay and Diffey1987), which also has a contribution from the UVA. The  
134 measurement data are recorded in 1 min intervals. Hence, the SL501 measured dose of the radiant  
135 energy  $Q_{ery}$  is calculated as the temporal and spectral integral of the convolution of the global solar  
136 spectral irradiance and the erythemal response, measured hemispherically at  $2\pi$ . For the  
137 erythemally weighted broadband albedo  $A_{ery}$ , the ratio of the hemispherically measured up-welling  
138 ( $\uparrow$ ) to down-welling ( $\downarrow$ ) UV solar radiation is then calculated as:

139

$$140 \quad A_{ery} = \frac{Q_{ery} \uparrow}{Q_{ery} \downarrow} \quad (1)$$

141

142 where the measured downwelling incoming irradiance includes both the direct and diffuse  
143 components, and the upwelling outgoing part consists of the hemispherically reflected global  
144 spectral diffuse radiance.

### 145 **2.3 The data collection systems in Sodankylä and Marambio**

146 The data collection systems in Sodankylä and Marambio (Fig. 4) are similar to each other. In  
147 Sodankylä, the UV-Albedo data collection system measures and saves data automatically in one  
148 minute interval. The system consists of sensors (2 x SL501A), loggers (Vaisala QML201), serial  
149 device servers (NPort 5150A) and an embedded linux computer (Moxa IA240). The logger  
150 measures raw data every 5 second for each sensor. Then the logger calculates one minute average



151 values and sends them to the linux-computer via the serial device server. The linux-computer sends  
152 then values to a database and then also saves them to a dayfile on an SD-card. All the data are  
153 available in the FMI Climate data base.

154 Similarly to Sodankylä, the UV-Albedo data collection system in Marambio measures and saves  
155 data automatically in one minute interval. The system consists of sensors (2 x SL501A and 1 x  
156 CMP11), a logger (Vaisala QML201) and an embedded linux computer (Moxa IA240). The logger  
157 measures raw data every 5 second for each sensor. Then the logger calculates one minute average  
158 values and sends them to the linux-computer. The linux-computer saves values to a dayfile on an  
159 SD-card. The SD-card is copied manually by the system user. The data are then sent to FMI by  
160 email, and stored in a server.

#### 161 **2.4 Calibration of the radiometers**

162 The four SL501 sensors needed for the purpose are maintained by FMI. The sensors are sent for  
163 calibration and for cosine and spectral response characterization to the Finnish Radiation and  
164 Nucleation Safety Authority (STUK). STUK determines the calibration factor (C) for each SL501  
165 sensor. The measured 1-min values are corrected by the calibration factor to gain the final  
166 measurement data. More details can be found in Meinander et al. (2008). The STUK procedure is  
167 the same for all the sensors used here.

168 At Sodankylä, the pair of sensors is changed each year to another pair of calibrated and maintained  
169 sensors. In Marambio, the sensors were changed to a new pair of calibrated and maintained sensors  
170 after the first year of measurements (2013). The current pre-calibrated Marambio SL501 sensors  
171 have been in use for 2014-2015. A post-calibration will be made when the Marambio sensors are  
172 transported back to Finland.

#### 173 **2.5 The biggest challenges in operating the bipolar measurements**

174 The major general challenges related to our bipolar measurement data, according to our experience,  
175 are listed in Table 1. These include the general challenges of: i) *Temperature effect*: all the sensors  
176 are temperature controlled; the temperature of the sensor needs to be controlled and monitored,  
177 because SL501 measurement values can be temperature affected; in the data files one column  
178 contains the sensor temperature recorded every minute, and these data are essentially needed in the  
179 QA/QC of the data; and ii) *Cosine error*: the opening angle of the SL501A is slightly restricted due  
180 to the sensor design, where the detector is situated lower than the filters (this is evident in the cosine  
181 responses of the sensors, too). This can have effects especially in polar region, characterized with



182 low solar elevation angles. As a consequence of the cosine error effect, some data at low solar  
183 elevation may be needed to be excluded from the scientific utilization.

184 In addition, at Sodankylä the biggest challenges in operating the measurements have been: i) *Wind*:  
185 Due to the very mild wind, snow accumulates on the sensors; some frost can be formed; ii)  
186 *Measurement horizon*: the operational albedo field is surrounded by trees. Especially due to the fact  
187 that as Sun is really low during snow time, the tree shadows can be very long. The tallest  
188 surrounding trees have been cut 19 October 2012 and that has been detected to cause a systematic  
189 rise in the level of the reflected radiation.; iii) *Calibration and maintenance of the sensors and*  
190 *operator access to the sensors*: The sensors are calibrated, maintained and placed in the albedo field  
191 every spring when the Sun appears. To prolong the lifetime of the sensors, they are not kept outside  
192 when the Sun is at lowest. Yet, there is already snow on the ground at the time of the installation,  
193 and although as little disturbance to the snow surface is caused as possible, it is impossible to keep  
194 the snow surface totally untouched during the installation. This may cause some error in the albedo  
195 measurements until the snow surface is fixed with new snow.

196 At Marambio, there are no obstacles surrounding the sensor. In turn, the biggest measurement  
197 challenges we have faced especially there have been: i) *Cleaness of the dome*: the surface of the  
198 quartz domes are not easy to maintain cleanest and free of dust, as the shelter is visited once a week.  
199 ii) *Wind and dust*: the dome may get scratches due to the ice, sand and dust drifting with the wind.  
200 iii) *Access* to the stand of the both sensors is uncomfortable. iv) *Wind*: As result of the high winds  
201 (50/70 Kt) can break the connector or produce radial shake, which may affect the levelling among  
202 other things. v) *Wind*: snow is sometimes blown away in one place revealing the bare ground (also  
203 under the albedo sensors).

204

### 205 **3 Scientific utilization of Sodankylä and Marambio data**

206 The purpose of the current paper is to document the materials and methods of the measurements to  
207 ensure a successful scientific utilization of the data in the future, and provide a literature reference  
208 for the measurements setup to be used, when the data are utilized. Hence, the focus of this paper is  
209 not to publish the existing data nor their scientific analysis. Although we do not present  
210 measurement data as such, we will give a short review of the scientific utilization of the snow UV  
211 albedo data (Chapter 3, Table 2), and discuss some future possibilities (Chapter 4).

212 The Sodankylä and Marambio measurement data consist of independent data of incoming and  
213 outgoing UV radiation, and snow UV albedo during snow time. The incoming solar irradiance



214 contains information on the state of the sky, and the outgoing reflected part about the surface  
215 properties. Therefore, in addition to the measurement challenges (see Chapter 2.5), there are several  
216 environmental factors that need to be considered in the scientific usage of the data. For example,  
217 snow albedo increases as the solar elevation decreases, i.e., albedo is SZA dependent.

218 The snow/ice properties affecting the albedo of clean and dirty snow are discussed in detail in  
219 Warren and Wiscombe (1980) and Wiscombe and Warren (1980). Albedo for clean snow at UV is  
220 expected to be 0.97-0.99, but albedo for dirty, melting or optically opaque snow can be significantly  
221 lower. Snow albedo varies with wavelength, and depends on a number of factors, such as the depth  
222 and age of the snow cover, snow grain size, solar zenith angle, and cloud cover. The BC snow  
223 albedo effect is the bigger the smaller the wavelength, i.e. many impurities absorb UV radiation.  
224 The scientific utilization of Sodankylä UV albedo data has revealed lower albedo values (0.5-0.7)  
225 than expected (~0.9) (Meinander et al. 2008 and 2013). Our preliminary analysis using Marambio  
226 data, in turn, has revealed highly variable snow albedo values, due to temporally and spatially  
227 changing snow conditions. Therefore, the scientific utilization of the Marambio data demands  
228 surface photographs to be combined with the measured albedo data.

### 229 *Analysis of the first Sodankylä UV albedo data*

230 As soon as the Sodankylä UV albedo measurements were started in spring 2007, a comprehensive  
231 analysis of Sodankylä data was made (Meinander et al. 2008). Ancillary meteorological automated  
232 weather station (AWS) data, and other available ancillary data, were used to investigate the various  
233 environmental factors related to the measured albedo signal. During the snow accumulation, the  
234 erythemal UV albedo was found at midday to be  $A=0.6-0.8$ . During melt it was  $A=0.5-0.7$ ,  
235 respectively. The snow albedo showed an unexpected diurnal decrease of 0.05 after midday, during  
236 the period of snow melt, when the sky was almost clear sky or with variable cloudiness. The decline  
237 recovered later, and it was solar azimuth angle asymmetric. This might indicate a change in snow  
238 properties. Two different independently measuring instruments confirmed this finding. In the  
239 following mornings, snow surface temperature was  $< 0\text{ }^{\circ}\text{C}$ . The diurnal change appeared for one to  
240 two hours. Surface snow daily metamorphosis can explain this. If the surface temperature increases,  
241 it can melt snow. Later, the surface would freeze.

### 242 *Empirical parameterizations*

243 The parameterizations obtained from the measurement data can be simple, yet useful. Using the  
244 data, we have gained an empirical relationship for Sodankylä snow grain diameter (D) as a function



245 of day of year ( $t$ ), and the daily maximum air temperature ( $T_{max}$ ). We have also the empirical  
246 relationship of albedo as a function of the height of the snowpack (Meinander et al. 2008).

247 ***Bipolar comparison of Sodankylä-Neumeyer data and physical reasons for the detected snow***  
248 ***albedo SZA asymmetry***

249 Soon after the Sodankylä snow UV albedo measurements were started, Sodankylä data were  
250 compared with the German Antarctic Neumayer Station ( $70^{\circ}39'S$ ,  $8^{\circ}15'W$ ) UV albedo data  
251 (Meinander et al. 2009). The same type of sensors, Biometer Model 501 from Solar Light Co.  
252 (SL501), were used.

253 In the Arctic, a 10 % decrease in albedo as a function of time within a day was found. The albedo  
254 changed from 0.77 to 0.67. In the Antarctic, the change was from 0.96 to 0.86. This is named as  
255 “snow albedo SZA asymmetry”. It means that snow albedo is different for the same SZA,  
256 depending of the time, and that is not due to changes in the irradiance (due to, e.g., cloudiness  
257 conditions). The asymmetry cases were analyzed according to meteorological data (air/surface/dew  
258 point temperature, and relative humidity). We found physical explanations for our observations.  
259 These were: 1. previous night’s low surface temperature combined with high relative humidity. This  
260 is favorable to frost. As a result, a higher albedo follows the next morning. 2. Previous night’s snow  
261 fall with higher reflectance. 3. Day time snow melt followed by night time refreeze.

262 We also listed there other possible sources of uncertainty, in the determination of the SZA  
263 asymmetry: i) the improper leveling of the sensor; ii) uneven snow surface (e.g., Antarctic sastrugi);  
264 iii) shadowing due to objects (containers, houses, trees, slopes) in the vicinity of the measurement  
265 site; iv) the different cosine behavior in different azimuthal planes of the diffusers. The detected UV  
266 albedo decline in Neumeyer data was ( $c = -0.024$ ):

267

$$268 \quad A = -0.0024 * SZA. \quad (2)$$

269

270 Earlier, Pirazzini (2004) suggested for Antarctic snow (using another independent data set) a SZA  
271 dependent snow albedo decline. The best afternoon fit for  $c$  was -0.003. We can conclude the value  
272 of  $c$  to be surprisingly similar in our independent data set.

273 ***Snow UV albedo at Sodankylä versus clean Arctic snow at  $87^{\circ}N$***



274 In Sodankylä, snow UV albedo values have been lower than expected. In Meinander et al. (2013),  
275 we found that in Sodankylä, albedo may be affected by high concentrations of BC, due to air masses  
276 originating from the Kola Peninsula, Russia. Mining and refining industries are located there (Fig. 9 in  
277 Meinander et al. 2013). As a comparison in clean Arctic environment, during the Arctic Ocean  
278 ASCOS-expedition (Finnish contribution to the Arctic Summer Cloud Ocean Study), we measured,  
279 using a NILU-UV radiometer, albedo values  $A = 0.91\text{--}0.92$  for UV and PAR at  $87^\circ\text{N}$  (Paatero et al.  
280 2009).

### 281 *Sodankylä snow UV albedo and organic and black carbon*

282 As part of the SNORTEX-2009 experiment in Sodankylä, snow albedo values were measured by  
283 three different independent measurement set ups (Meinander et al. 2013). In addition to the SL-501  
284 UV albedo, a double monochromator spectroradiometer Bentham for UV albedo, and pyranometer  
285 setup for VIS albedo were used. UV albedo (at 330 nm) was detected to decrease from 0.65 to 0.45,  
286 while most intensive snow melt took place. At visible wavelengths (450 nm), albedo changed from  
287 0.72 to 0.53. Low albedo was confirmed by three independent simultaneous measurement devices.  
288 We explained the low albedo values to be due to 1. large snow grain sizes (with diameter of 3 mm).  
289 2. Meltwater increasing the effective grain size. 3. Light absorbing impurities (LAI) in the snow. At  
290 the time of albedo measurements, snow contained 87 ppb of elemental carbon (black carbon, BC).  
291 The organic carbon concentration was 2894 ppb. EC/OC analysis were performed using the  
292 thermal–optical method. It was shown, that high EC in snow was due to air masses originating from  
293 the Kola Peninsula, Russia. The place is known for mining and refining industries.

294

## 295 **4 Modeling and remote sensing applications**

### 296 **4.1 Snow UV albedo and BC: soot in snow absorbs the most at UV**

297 The black carbon (BC) has been estimated to be the second most important human emission after carbon  
298 dioxide, in terms of its climate forcing in the present-day atmosphere (Bond et al. 2013). The effect on  
299 reflectance of BC deposited on snow surface is the bigger the smaller the wavelength, i.e. the albedo effect of  
300 BC is the biggest at UV (Fig 5, and Fig. 10 in Meinander et al. 2013). Based on the Soot on Snow  
301 experiment (SoS-2013) in Sodankylä, we have also recently presented a new hypothesis (Meinander et al.  
302 2014b) that soot may decrease the melt water retention capacity, and thus decrease the snow density of  
303 melting snow.

### 304 **4.2 Satellite applications**



305 Satellite programmes produce measurements of atmospheric compounds and related parameters that  
306 can be used together with the GAW network measurements. Putting together the highly accurate  
307 local measurements from GAW ground-based stations and the satellite measurements with larger  
308 coverage, a more complete picture can be achieved. The Committee on Earth Observation (CEOS)  
309 has developed a strategy for such co-operation within an integrated system for monitoring of the  
310 atmosphere (WMO 2001).

311 UV surface albedo is also a key parameter for applications using RT modeling, such as satellite  
312 retrieval algorithms (Arola et al., 2003, Tanskanen and Manninen, 2007). The measurement set up  
313 allows an independent use of the incoming and outgoing UV radiation. Therefore, the irradiance  
314 data can help filling gaps in the incoming UV radiation measured within the Argentinian-Spanish-  
315 Finnish co-operative NILU-UV Antarctic network (Redondas et al. 2008). Previously, those NILU-  
316 UV data were compared with the overpass OMI UV satellite data (see Meinander et al. 2014a), and  
317 the current data serves equally well for the same purpose.

318

## 319 **5 Conclusions**

320 We have successfully operated broadband radiometers for measuring incoming and outgoing  
321 ultraviolet radiation in the harsh polar environmental conditions of Sodankylä, north of the Arctic  
322 circle, and Marambio in the Antarctic Peninsula. Here we described the design and operation  
323 demands from the bipolar point of view. The measurements in Sodankylä were started as part of  
324 the International Polar Year. The Marambio Antarctic measurements are applied for investigating  
325 the incoming radiation, ground albedo during snow and no snow, and have a great potential to serve  
326 satellite applications, too. Another important application may be expected from the fact that light  
327 absorbing impurities deposited in snow can have bigger absorbance at the wavelengths of UV.

328 In the polar regions, the monitoring of incoming ultraviolet radiation is of special interest due to its  
329 connection to stratospheric ozone depletion (often called the “ozone hole area”, when total ozone is  
330 less than 220 DU). The year 2015 has the third largest ozone hole on record according to this  
331 criterion (WMO 2015a and 2015b), showing that the importance of ozone depletion is still actual.

332 Here we document, for the first time, the practical challenges in operating these measurement  
333 systems in Sodankylä and Marambio. These challenges need to be carefully taken into account  
334 when utilizing the data.



335 The data have been agreed to be submitted to the WMO GAW World Ozone and UV Radiation  
336 Data Centre WOUDC (<http://www.woudc.org/>), and to the EUVDB database  
337 (<http://uv.fmi.fi/uvdb/>), where they will be freely available for further scientific utilization.

338

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343

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417 Table 1. Summary of the challenges of the bipolar UV radiation measurements in Sodankylä  
 418 and Marambio.

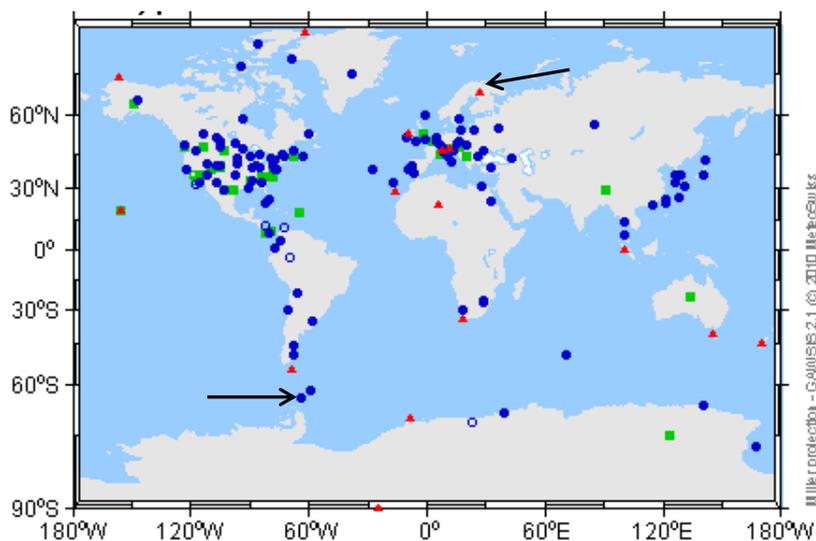
Challenge	Sodankylä	Marambio
Temperature	The temperature of the sensor needs to be controlled and the recorded sensor temperature to be used in the QA/QC of the data.	The temperature of the sensor needs to be controlled and the recorded sensor temperature to be used in the QA/QC of the data.
Low solar elevation	Cosine error of the sensor may cause a need to exclude low elevation data from the analysis	Cosine error of the sensor may cause a need to exclude low elevation data from the analysis
Wind	Due to the lack of wind, snow accumulates on the sensors; some frost can be formed.	As result of the high winds (50/70 Kt) can break the connector or produce radial shake, which may affect the levelling among other things.
Maintenance	Snow surface is not totally untouched during the installation. This may cause some error in the data until new snow.	The surface of the quartz domes are not easy to maintain cleanest and free of dust, as the shelter is visited once a week.
Measurement horizon	Trees surround the area. As Sun is low during snow time, the tree shadows can be long. Surrounding trees were cut 19 Oct 2012.	Not a problem, the horizon is open.
Dust	Not a problem.	The dome may get scratches due to the ice and sand and dust; surfaces of the quartz domes are not easy to maintain cleanest and free of dust. Snow can sometimes be dirty.
Snow surface	Seasonal snow cover, snow height varies.	Snow is sometimes blown away revealing the bare ground under the downlooking sensor



419 Table 2. Summary of Arctic Sodankylä snow SL-501 UV albedo findings, and comparison results.

Snow UV albedo findings	Reference
Sodankylä midday erythemally weighted SL-501 UV albedo was 0.6 - 0.8 in the accumulation period, and 0.5 - 0.7 during melt.	Meinander et al., (2008)
Sodankylä daily SL-501 UV snow albedo as a function of snow height ( $h$ ) for $56 < SZA < 60$ degrees during the melt $A = -6E - 0.5h^2 + 0.0114h + 0.1809$ .	Meinander et al. (2008)
Diurnal decrease of 0.05 in Sodankylä snow SL-501 UV albedo soon after midday, and recovery thereafter, possibly due to snow metamorphism.	Meinander et al. (2008)
SZA asymmetry in snow SL-501 UV albedo: Up to 10 % decrease in albedo as a function of time within a day, ranging from 0.77 to 0.67 in the Arctic Sodankylä, and from 0.96 to 0.86 in the Antarctic Neumeyer station. Physical snow property related explanations given.	Meinander et al. (2009)
Arctic cleans snow, comparison NILU-UV snow albedo measurements at 87 deg N, $A = 0.91-0.92$ for UV and PAR.	Paatero et al. (2009)
Sodankylä melting snow low albedo values (Bentham $\sim 0.5-0.7$ , SL-501 $\sim 0.4-0.5$ , and CM14 $\sim 0.6-0.75$ ) can be explained by 1. large snow grain sizes up to $\sim 3$ mm in diameter; 2. meltwater surrounding the grains and increasing the effective grain size; 3. absorption caused by impurities in the snow, with concentration of elemental carbon (black carbon) in snow of 87 ppb, and organic carbon 2894 ppb, at the time of albedo measurements.	Meinander et al. (2013)
Sodankylä snow albedo: Empirical albedo conversion between visible and UV albedo: $A(VIS) = 1.1602A(UV-B) - 0.0213$ , ( $R^2 = 0.6012$ ).	Meinander et al. (2013)
10 % daily melt time asymmetry in Sodankylä snow UV albedo.	Meinander et al. (2013)

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421  

	GAW Global Station		GAW Regional Station		Contributing Station
Open symbols denote closed or inactive stations.					

422

423 Figure 1. The UV radiation measurement stations of the WMO GAW network; Sodankylä and  
424 Marambio stations are indicated with black arrows (map downloaded using  
425 <http://gaw.empa.ch/gawsis/>).



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427

428 Figure 2. Sodankylä albedo field (16 m x 16 m) protected with fences and surrounded by pine trees.

429 The albedo sensors (on the left) are attached to a pole facing to the South.

430



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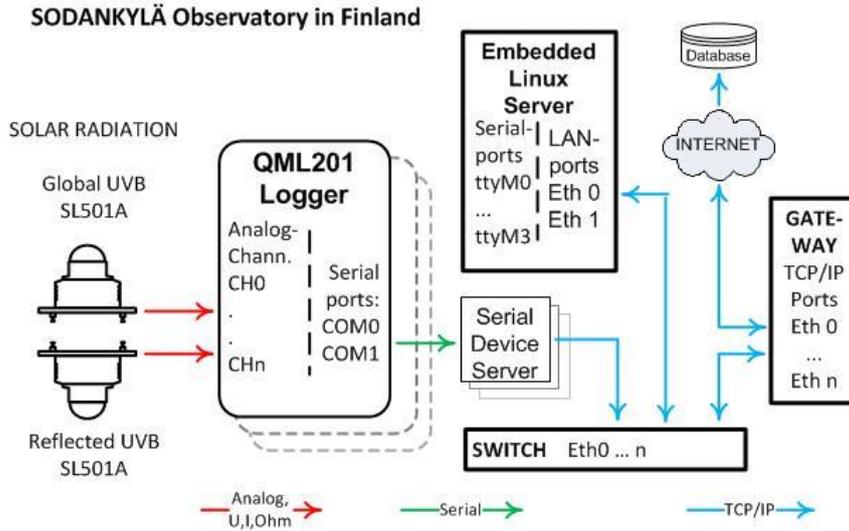
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433 Figure 3. Marambio UV albedo measurement place and the environmental conditions for the  
434 measurement of outgoing radiation.

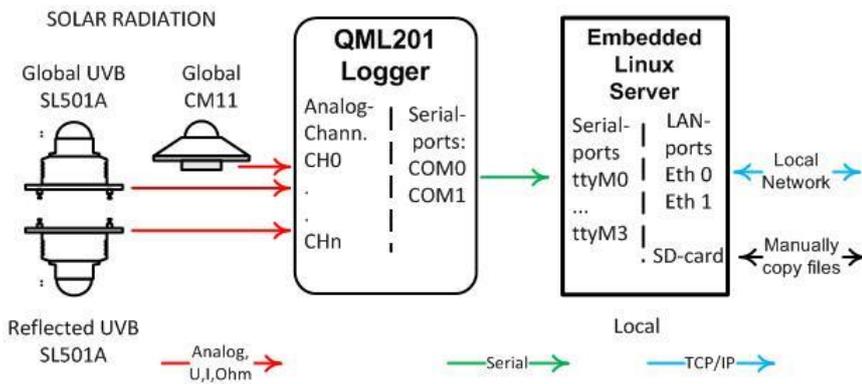
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### The block diagram of UV -Albedo measurements



### MARAMBIO Observatory in AntArctis



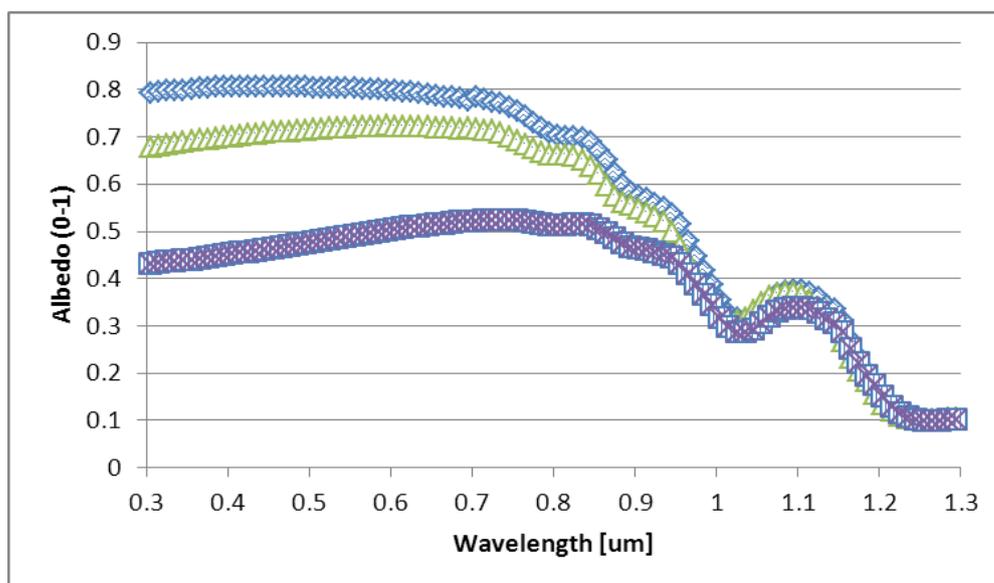
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438 Figure 4. The block diagram of incoming and outgoing solar UV radiation measurements in

439 Sodankylä and Argentina using the SL-501A sensors.

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443 Figure 5. The effect of the light-absorbing BC on snow albedo is the biggest at the UV wavelengths.  
444 The highest reflectivity is calculated for snow with no BC (upper curve, blue). If the amount of BC  
445 is increased to 200 ppb and the mass absorption scaling factor is the default value 1.0, spectral  
446 albedo is decreased, the more the smaller the wavelength (middle curve, green). Albedo is further  
447 decreased, if for the same BC amount only the mass absorption scaling factor is increased (lower  
448 curve, purple). Otherwise, the blue, green and purple curves are calculated using the same input  
449 values. The figure demonstrates that it is both the BC concentration and the MAC values together  
450 that affect the simulated spectral albedo values. The simulation was calculated using the SNICAR  
451 model by Flanner et al. (2007).