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On the reflectance spectroscopy of snow

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Abstract

We propose a system of analytical equations to retrieve snow grain size and absorption coefficient of pollutants from snow reflectance or snow albedo measurements in the visible and near-infrared regions of the electromagnetic spectrum. It is assumed that ice grains and impurities (e.g., dust, black and brown carbon) are externally mixed. The system of nonlinear equations is solved analytically in the assumption that impurities influence registered spectra in the visible and not at near-infrared (and vice versa for ice grains). The theory is validated using spectral reflectance measurements and albedo of clean and polluted snow at various locations (Antarctica Dome C, European Alps). The technique to derive the snow albedo (plane and spherical) from reflectance measurements at a fixed observation geometry is proposed. The technique also enables the simulation of hyperspectral snow reflectance measurements in the broad spectral range from ultraviolet to the near-infrared for a given snow surface in the case,

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if the actual measurements are performed at restricted number of wavelengths (2-4, depending on the type of snow and the measurements system).

1. Introduction

The reflective properties of clean and polluted snow are of importance for various applications including climate (Hansen and Nazarenko, 2007) and environmental pollution (Nazarenko et al., 2017) studies. The spectral snow reflectance is usually studied in the framework of the radiative transfer theory. The application of the numerical methods for the solution of the radiative transfer equation for snow layers has been performed by Mishchenko et al. (1999), Stamnes et al. (2011), and He et al. (2018) among others. The approximate solutions of the radiative transfer equation useful for snow optics and spectroscopy applications have been developed by Warren and Wiscombe (1980), Wiscombe and Warren (1980) and Kokhanovsky and Zege (2004). In this work, we propose an analytical snow albedo and reflectance model, which can be used to derive snow optical and microphysical properties using measurements at just one to four wavelengths in the visible and near–infrared depending on the measurement system and type of snow. In particular, we present the method for the determination of snow grain size, absorption Angström coefficient and spectral absorption coefficient of impurities embedded in the snow matrix assuming an external mixture of snow grains and impurities. A technique to derive the snow albedo from reflectance measurements is also presented. The absorption and extinction of light by snow grains is treated in the framework of a geometrical optical approximation. The absorption coefficient of impurities is modeled using the Angström power law. All derivations are performed in the framework of the asymptotic radiative transfer theory (see, e.g., Kokhanovsky and Zege, 2004, Zege et al., 2011).

2. Theory

2.1 The snow reflectance

The snow reflectance R (equal to unity for ideal white Lambertian reflectors) can be presented in the following way using approximate asymptotic radiative transfer theory (Kokhanovsky and Zege, 2004):

$$R = r_s^{\,x}, \tag{1}$$

where $x = u(\mu_0)u(\mu)/R_0$, R_0 is the reflectance of a semi-infinite non-absorbing snow layer, $u(\mu_0) = \frac{3}{7}(1+2\mu_0)$, μ_0 is the cosine of the solar zenith angle, μ is the cosine of the viewing zenith angle, r_s is the snow spherical albedo:

$$r_s = e^{-y}, \tag{2}$$

where

$$y = 4\sqrt{\frac{\beta}{3(1-g)}}, \tag{3}$$

g is the asymmetry parameter, β is the probability of photon absorption defined as the ratio of absorption κ_{abs} and extinction κ_{ext} coefficients:

$$\beta = \frac{\kappa_{abs}}{\kappa_{ext}}, \tag{4}$$

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where

$$\kappa_{abs} = \kappa_{abs}^{ice} + \kappa_{abs}^{pol}. \quad (5)$$

The first and second term in Eq. (5) correspond to the ice grains and pollutants, respectively. We assume that scattering of light by impurities is much smaller than that by ice grains and, therefore (Kokhanovsky and Zege, 2004),

$$\kappa_{ext} = \frac{3c}{d}. \quad (6)$$

Here, $d = 1.5\bar{V}/\bar{S}$ is the effective diameter of ice grains, $\bar{V}$ is the average volume of grains, $\bar{S}$ is their average projected area averaged over all directions, equal to $\sum/4$ for convex particles in random orientation , where $\sum$ is the average surface area and c is the volumetric concentration of the snow grains.

It follows as $\alpha d \to 0$ in the visible and near infrared (Kokhanovsky and Zege, 2004)that :

$$\kappa_{abs}^{ice} = A\alpha c, \quad (7)$$

where A is the grain shape-dependent parameter and $\alpha = \frac{4\pi\chi}{\lambda}$, where χ is the imaginary part of the ice refractive index at the wavelength λ.

We present the absorption coefficient of pollutants in snow as

$$\kappa_{abs}^{pol}(\lambda) = \kappa_0 \tilde{\lambda}^{-m} , \quad (8)$$

where $\kappa_0 \equiv \sigma_{abs}^{pol}(\lambda_0)$, $\tilde{\lambda} = \lambda/\lambda_0$. We will assume that $\lambda_0 = 1\ \mu m$.

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It follows from Eqs. (4)-(8):

$$\beta = \frac{A\alpha d}{3} + \beta^{pol} \quad , \tag{9}$$

where

$$\beta^{pol} = \frac{\kappa_0 \tilde{\lambda}^{-m} d}{3c} \tag{10}$$

and therefore:

$$y = \frac{4}{3}\sqrt{\frac{(A\alpha + \kappa_0 \tilde{\lambda}^{-m} c^{-1})d}{1-g}} \; . \tag{11}$$

Let the parameter $z = y^2$, from which it follows that:

$$z = (\alpha + f\tilde{\lambda}^{-m})l \, , \tag{12}$$

where

$$f = \frac{\kappa_0^*}{A} \tag{13}$$

$\kappa_0^* = \kappa_0 / c$ and

$$l = \xi d \tag{14}$$

is the effective absorption length (EAL) and

$$\xi = \frac{16A}{9(1-g)} \tag{15}$$

is a grain shape (but not the grain size) dependent parameter.

The parameter l can be determined directly from reflectance or albedo measurements, enabling also the determination of the grain diameter $d = l/\xi$ assuming a particular shape of grains. It has

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been found that the asymmetry parameter of crystalline clouds is usually in the range 0.74-0.76 in the visible (Garret, 2008). The asymmetry parameter g for snow has not been measured before but we shall assume that it is close to that in crystalline clouds and adopt the value 0.75. It follows from experimental studies of Libois et al. (2014) that $A=1.6$ on average. Therefore, it follows (see Eq. 15): $\xi \approx 11.38$.

Using the EAL l, equations for the snow reflectance and spherical albedo may be simplified as:

$$R = R_0 \exp(-x\sqrt{(\alpha + f\tilde{\lambda}^{-m})l}), \quad (16)$$

$$r_s = \exp(-\sqrt{(\alpha + f\tilde{\lambda}^{-m})l}). \quad (17)$$

The plane albedo can be derived as well (Kokhanovsky and Zege, 2004):

$$r = \exp(-u(\mu_0)\sqrt{(\alpha + f\tilde{\lambda}^{-m})l}). \quad (18)$$

The relationship between the albedo and the reflectance R can be found elsewhere (Kokhanovsky and Zege, 2004). It follows from Eq. (16) that the spectral reflectance of polluted snow is determined by four parameters: l, R_0, f, m. They can be estimated from the measurements of reflectance at four wavelengths. This also enables the determination of the spectral reflectance (and albedo, see Eq.(18)) at the visible and near – infrared wavelengths at an arbitrary λ. It follows:

$$R_1 = R_0 \exp(-x\sqrt{(\alpha_1 + f\tilde{\lambda}_1^{-m})l}), \quad (19)$$

$$R_2 = R_0 \exp(-x\sqrt{(\alpha_2 + f\tilde{\lambda}_2^{-m})l}) \quad (20)$$

$$R_3 = R_0 \exp(-x\sqrt{(\alpha_3 + f\tilde{\lambda}_3^{-m})l}) \quad (21)$$

$$R_4 = R_0 \exp(-x\sqrt{(\alpha_4 + f\tilde{\lambda}_4^{-m})l}) \tag{22}$$

where the numbers 1, 2, 3, and 4 signify the wavelengths used. Equations (19)-(22) can be used to compute four unknown parameters given above, and, therefore, determine reflectance and albedo at any wavelength in the visible and the near-infrared using Eqs. (16)-(18). Let us assume that the spectral channels are selected in a way that the effects of ice absorption can be neglected in the first two channels (λ_1, λ_2) and effects of absorption by pollutants are negligible in the second pair of channels (λ_3, λ_4). This situation is typical of not heavily polluted snow. Then it follows instead of Eqs. (19)-(22):

$$R_1 = R_0 \exp(-x\sqrt{f\tilde{\lambda}_1^{-m}l}), \tag{23}$$

$$R_2 = R_0 \exp(-x\sqrt{f\tilde{\lambda}_2^{-m}l}), \tag{24}$$

$$R_3 = R_0 \exp(-x\sqrt{\alpha_3 l}), \tag{25}$$

$$R_4 = R_0 \exp(-x\sqrt{\alpha_4 l}). \tag{26}$$

Eqs. (25), (26) can be used to find the pair (l, R_0):

$$R_0 = R_3^{\varepsilon_1} R_4^{\varepsilon_2}, \; l = \frac{1}{x^2 \alpha_4} \ln^2 \left[\frac{R_4}{R_0} \right], \tag{27}$$

where $\varepsilon_1 = 1/(1-b), \varepsilon_2 = 1/(1-b^{-1}),\ b = \sqrt{\alpha_3 / \alpha_4}$. Then it follows from Eqs. (23), (24) that:

$$m = \frac{\ln(p_1 / p_2)}{\ln(\lambda_2 / \lambda_1)}, \tag{28}$$

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$$f = \frac{p_1 \tilde{\lambda}_1^m}{x^2 l}, \quad (29)$$

where $p_k = \ln^2(R_k / R_0)$. In case of the absence of pollutants, Eqs. (27) remain valid. However, the parameters *m* and *f* are undefined and $R = R_0 \exp(-x\sqrt{\alpha l})$.

One may also derive the impurity absorption coefficient at the wavelength λ_0 normalized to the concentration of ice grains *c* (see Eq. (13)):

$$\kappa_0^* = Af, \quad (30)$$

where *f* is given by Eq.(29). The normalized absorption coefficient at each wavelength can also be found using Eqs. (8), (28), (30).

To determine the concentration of pollutants (c_p) one must either know in advance or determine the impurity volumetric absorption coefficient defined as:

$$K(\lambda_0) = \frac{\bar{C}_{abs}(\lambda_0)}{\bar{V}}, \quad (31)$$

where $\bar{C}_{abs}$ is the average absorption cross section of impurities and $\bar{V}$ is the averge volume of absorbing impurities. Namely, it follows by definition:

$$c_p = \frac{\kappa_0}{K(\lambda_0)} \quad (32)$$

and

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$$\mathbb{C} = \frac{\kappa_0^*}{K(\lambda_0)}, \qquad (33)$$

where $\mathbb{C} = c_p / c$.

The value of $K(\lambda_0)$ can be found, if one knows the type of pollutants and their microphysical properties. In particular, it follows for the impurities much smaller than the wavelength λ_0 (van de Hulst, 1981) that :

$$K(\lambda_0) = F\alpha_{pol}(\lambda_0), \qquad (34)$$

where

$$\alpha_{pol}(\lambda_0) = \frac{4\pi\chi_{pol}(\lambda_0)}{\lambda_0} \qquad (35)$$

is the pollutant bulk absorption coefficient, $\chi_{pol}(\lambda_0)$ is the imaginary part of pollutant refractive index and n_{pol} is the real part of the pollutant refractive index,

$$F = \frac{9n_{pol}}{\left(n_{pol}^2 + 1 - \chi_{pol}^2\right)^2 + 4n_{pol}^2\chi_{pol}^2} \quad . \qquad (36)$$

It follows that $F = 0.9$ for soot (assuming that n=1.75, $\chi_{pol} = 0.47$ in the visible). One can see that $\mathbb{C}$ can be found if one knows the refractive index of absorbing Rayleigh particles in advance.

In particular, it follows for soot impurities that:

$$\mathbb{C} = \frac{Ap_1\tilde{\lambda}_1^m}{x^2 lF\alpha_{pol}(\lambda_0)}. \qquad (37)$$

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In case of non-Rayleigh scatterers, one needs to know not only the refractive index but also the particle size distribution and shape of particles, enabling the determination of the impurity volumetric absorption coefficient $K(\lambda_0)$ and, therefore, the normalized concentration of impurities

$$\mathbb{C} = \frac{Ap_1\tilde{\lambda}_1^m}{x^2 lK(\lambda_0)}. \tag{38}$$

2.2. The snow albedo

In case if the plane albedo is the measured physical quantity one needs to find only three constants: l, f, m.

The respective analytical equations can be presented as:

$$r_1 = \exp(-u(\mu_0)\sqrt{(\alpha_1 + f\tilde{\lambda}^{-m})l}), \tag{39}$$

$$r_2 = \exp(-u(\mu_0)\sqrt{(\alpha_2 + f\tilde{\lambda}_2^{-m})l}), \tag{40}$$

$$r_3 = \exp(-u(\mu_0)\sqrt{(\alpha_3 + f\tilde{\lambda}_3^{-m})l}). \tag{41}$$

We shall assume that the last channel is not influenced by impurities and the first two channels are not influenced by the absorption of light by grains. Then it follows that:

$$r_1 = \exp(-u(\mu_0)\sqrt{f\tilde{\lambda}_1^{-m}l}), \tag{42}$$

$$r_2 = \exp(-u(\mu_0)\sqrt{f\tilde{\lambda}_2^{-m}l}), \tag{43}$$

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$$r_3 = \exp(-u(\mu_0)\sqrt{\alpha_3 l}). \tag{44}$$

The EAL can be found from Eq. (44):

$$l = \frac{\ln^2 r_3}{u^2(\mu_0)\alpha_3}. \tag{45}$$

It follows from Eqs. (42), (43) that:

$$m = \frac{\ln(\psi_2/\psi_1)}{\ln(\lambda_1/\lambda_2)},\ f = \frac{\psi_1 \tilde{\lambda}_1^m}{u^2(\mu_0)l}, \tag{46}$$

where $\psi_k = \ln^2 r_k$.

In case of unpolluted snow, one derives:

$$r = \exp(-u(\mu_0)\sqrt{\alpha l}). \tag{47}$$

Eq. (45) can be used to find the effective absorption length and, therefore, the spectral albedo of unpolluted snow at any wavelength using Eq. (47).

One can derive from Eq. (45):

$$\sigma_l = \upsilon \sigma_{r_3},\ \upsilon = \frac{2}{\ln r_3}, \tag{48}$$

where σ_l is the relative error in the determination of the effective absorption length and σ_{r_3} is the relative error of the plane albedo measurement at the wavelength λ_3. Taking into account that $\ln r_3 \le 0$, one concludes that the positive bias of the measured plane albedo will lead to the underestimation of the effective absorption length (and, therefore, snow grain size) with the enhancement coefficient υ. The enhancement coefficient is larger for larger values of albedo (smaller particles or shorter wavelengths). Similar analysis for the concentartion of pollutants is more involved because the errors of measurements at three channels influence the concentration of pollutants determination. In particular, one finds that the positive bias in the measured albedo in the visible will lead to the underestimation of the concentration of pollutants (assuming that the grain size is exactly known). It should be pointed out that in most cases the concentration of pollutants is so small that it can not be assessed using optical instruments (change in reflectance is inside experimental measurement error). This issue has been discussed by Zege et al. (2011) and Warren (2013). Similar conclusions hold also if the reflectance (and not albedo) is the measured quantity.

3. Experiment

3.1 The measurements of the plane albedo

We have applied the technique developed above to the measured spectral plane albedo both for polluted and pure snow. Therefore, in-situ spectral albedo measurements were obtained from two different field sites located in Antarctica (clean snow) and the French Alps (polluted snow).

The spectral albedo of pure snow (very low amount of impurities) was measured at Dome C (75°5' S, 123°17' E), in Antarctica using an automated spectral radiometer (Libois et al., 2015; Picard et al., 2016; Dumont et al., 2017). The instrument is composed of two individual heads located approximately 1.5 m above the surface. Each head contains two cosine receptors facing upward and downward, which receive the incident solar radiation and the reflected radiation. The collectors are connected to a MAYA2000 PRO Ocean Optics spectrometer with fibre optics

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through an optical switch. Radiation is measured over 350-2500 nm spectral range with an effective spectral resolution of 3 nm. Albedo was calculated as the ratio of the upward and downward spectral irradiance. The full description of the instrument and the processing steps to calculate the spectral albedo are given by Picard et al. (2016). The spectral albedo measurements used here were made on the 10^{th} January 2017, with a solar zenith angle of 63.2º, during clear sky conditions assessed by ground observations.

The spectral albedo of a spring alpine snowpack was measured at the Col du Lautaret field site (45°2' N, 6°2' E, 2100 m a.s.l.) in the French Alps. The measurements were performed using a non-automated version of the spectrometer system described above. The hand-held instrument has a single light collector, located at the end of 3 m boom placed 1.5 m above the surface. The boom is rotated by the operator to successively acquire the downward and upward solar radiation. Five spectral albedo measurements were obtained on 12th April, 2017 across a 100 m transect, in attempt to account for spatial variability. The measurements were acquired in clear sky conditions, with a solar zenith angle varying between 47.9º and 52.2º. The five spectral albedo measurements were averaged for the comparison with the theory.

The results of inter-comparison of measurements and the theory presented above are illustrated in Fig.1. The parameters l, f, m have been found from Eqs. (42)-(44) and the measurements at the wavelengths $\lambda_1 = 400nm, \lambda_2 = 560nm, \lambda_3 = 1020nm$. At all measurement sites the results of the inter-comparison are excellent and similar to that presented in Fig.1. Therefore, the theory can be used to derive snow optical and microphysical properties even for polluted snowpack. The derived spectral probability of photon absorption for the case shown in Fig. 1 is presented in Fig.2. The derived absorption coefficient (assuming c=1/3), the grain diameter and the absorption Angström parameter for five samples are listed in Table 1 (lines 1-5). It follows that

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the value of *m* is in the range 2.4 - 4.1 consistent with the identified presence of dust particles in snow (Doherty et al., 2010). The pure black carbon impurities have the values of *m* close to one. The grain diameter is in the range 1.5-1.9 mm consistent with low values of snow albedo at 1020nm (see Fig.1). The results of the application of the technique to the pure snow (no pollution) albedo measured in Antarctica are illustrated in Fig.3. One can see that the agreement is excellent and the value of snow albedo depends just on one parameter – the characteristic length, which has been derived at a single wavelength (1020nm). The derived grain diameter for the case presented in Fig.3 is equal to 0.5mm.

3.2 The measurements of the spectral reflectance

The application of the developed theory to the measurements of the spectral reflectance is presented in Fig.4 for two locations with different dust load (39.6ppm and 107.4ppm). The spectral reflectance of snow was measured in the European Alps (45°55'56.70"N; 45°55'56.70"N) at the solar zenith angle equal to 52 degrees. The measurements were made on March 14th 2014, after a major transport and deposition of mineral dust from the Saharan desert. The event was very intense, and it was reported in the recent scientific literature regarding snow optical properties, (Di Mauro et al., 2015; Dumont et al., 2017), atmospheric chemistry and physics (Belosi et al., 2017), and also microbiology (Weil et al., 2017). The dust transport event deposited fine mineral dust particles from the atmosphere via wet deposition, according to the BSC-DREAM-8b model (Basart et al., 2012). Spectral measurements of snow were made using a field spectrometer (Field Spec Pro, Analytical Spectral Devices, ASD). This instrument features a spectral range of 350-2500 nm, a full width at half maximum of 5–10 nm, and a spectral resolution of 1 nm. Data presented here were collected under clear sky conditions at noon. Incident radiation was estimated using a Lambertian Spectralon panel. Reflected radiance was divided by incident radiance, and the hemispherical conical reflectance factor (HCRF) was calculated for three plots containing 0.92, 39.6 and 107.4 ppm of dust. Dust concentration was measured with a Coulter Counter by integrating particles with a diameter smaller than 18 μm. Spectral measurements were performed at nadir using a bare optical fiber (field of view of 25°) at 80 cm from the snow sample. Both the optical fiber and the spectralon panel were equipped with an optical level. Further details on this dataset can be found in Di Mauro et al. (2015).

One can see that the theory works well not only for the albedo measurements (see the previous section) but also for the reflectance measurements for polluted snow layers. In particular, our results are closer to the measurements as compared to the theoretical model described by Flanner et al. (2007) (see Fig.4b in Di Mauro et al., 2015). The derived parameters are given in Table 1 (lines 6-7). The value of m is *4.1* for the first case and it is *6.4* for the second case with high dust concentration. Because the difference is quite large for the close locations we conclude that snow also contained other pollutants (say, soot) and the determined value of *m* represents the combined effect with larger values of *m* for larger concentrations of dust, which is consistent with other observations of this parameter in snow (Doherty et al., 2010). The retrieved absorption coefficient of snow pollutants (at the wavelength $\lambda^* = 560nm$) is 0.1191 m^{-1} for the dust concentration 39.6ppm and it is 0.3123 m^{-1} for the dust concentration of 107.4 ppm. Assuming that the dust chemical composition and also the dust particle size distribution are the same at both locations we can assume that the ratio of absorption coefficients at two locations should be equal to the ratio of dust concentrations. This is really so with the difference just 3%

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which is within the accuracy of experimental measurements. The mass absorption coefficient can be estimated using:

$$K_m = \frac{\kappa_{abs}^{pol}\left(\lambda^*\right)}{\mathbb{C}\rho c}, \tag{49}$$

where ρ is the density of the substance of impurities. Assuming that:

$$\rho = 2.62 g / cm^3 \text{ (as for quartz)}, c = 1/3,\ \mathbb{C} = 107.4\, ppm \text{ and } \kappa_{abs}^{pol}\left(\lambda^*\right) = 0.3123 m^{-1}, \tag{50}$$

one can derive that:

$$K_m = 0.0033 m^2 / g, \tag{51}$$

which is consistent with the values of MAC given by Utry et al.(2015) (e.g., $0.0023 m^2 / g$ for quartz and $0.0051 m^2 / g$ for illite (see their Table 1)).

4. Conclusions

In this work, we have presented a sequence of analytical equations, which can be used to determine the snow grain size, the absorption coefficient of impurities, and the absorption Angström coefficient of surface snow impurities from the snow reflectance measured at four wavelengths. Two of them are located in the visible and two - in the near infrared as suggested by Warren (2013). In principle, the refractive index of dust and dust size distribution can be also determined using derived spectral absorption coefficient of dust and assuming the shape of dust particles. However, we did not make an attempt for such retrievals in this work. The method for

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the retrieval of the complex refractive index and single scattering optical properties of dust deposited in mountain snow based on exact radiative transfer calculations has been proposed by McKenzie Siles et al. (2016) in the assumption that local optical properties of dust grains can be simulated assuming the spherical shape of particles. Their method is based on the extraction of dust grains from snowpack. Our technique does not require such a complicated procedure.

We have demonstrated how snow albedo can be derived from spectral reflectance measurements avoiding complicated integration with respect to the observation geometry (azimuth, viewing angle). The last point is useful for the determination of the snow *albedo* from spectral *reflectance* measurements (say, from aircraft or satellite) at a fixed observation geometry. Although the comprehensive validation of the retrievals has not been attempted, we have found that the ratio of derived absorption coefficients of pollutants at two concentrations is close to the ratio of pollutant concentrations derived independently, which indeed should be the case taking the proximity of two measurement sites with different dust loads. The general validity of the approach is proven using field measurements (Alps, Antarctica) of both spectral reflectance and plane albedo.

The determination of the effective absorption length l (unlike the effective grain diameter d) both from reflectance and albedo measurements is practically insensitive to *apriori* unknown shape of ice crystals. Therefore, this length may be useful for the characterization of snowpack microstructure (in addition to the grain size d). The results presented in this work are useful for the interpretation of snow properties using both reflectance spectroscopy (Hapke, 2005) and imaging spectrometry (Dozier et al., 2009).

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Tables

Table 1. The derived snow parameters for the five samples. The value of *c* is assumed to be equal 1/3, which leads to the extinction length ($l_{ext} = 1/\sigma_{ext}$) to be equal to the effective grain diameter *d*. The absorption coefficient is given at the wavelengths λ_0=1000nm and $\lambda^* = 560nm$.

N	κ_0, m^{-1}	$\kappa_{abs}^{pol}(\lambda^*), m^{-1}$	*m*	*d,mm*
1	0.0182	0.1954	4.1	2.1
2	0.0342	0.2668	3.5	2.2
3	0.1073	0.7194	3.3	1.7
4	0.0769	0.5324	3.3	1.9
5	0.0943	0.3848	2.4	2.2
6	0.0111	0.1191	4.1	2.5
7	0.0077	0.3123	6.4	1.5

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Figures

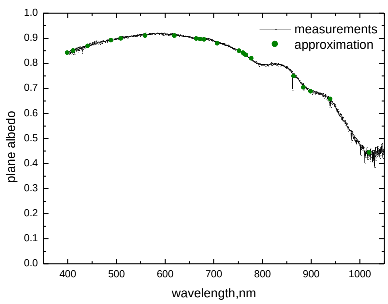

Fig.1. The intercomparison of theory (symbols) with experimental measurements of plane albedo (line) performed in French Alps (45°2' N, 6°2' E, 2100 m *a.s.l.)* for the dust – loaded snowpack. The parameters *l, f, m* have been derived from the measurements at 400, 560, and 1020nm.

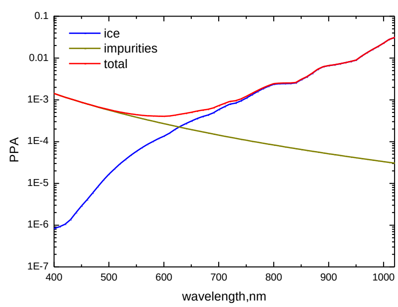

Fig.2. The derived spectral probability of photon absorption for the case presented in Fig.1.

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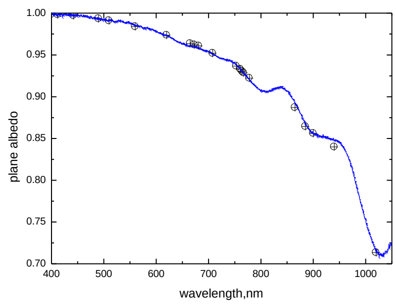

Fig.3 The inter-comparison of theory (symbols) with experimental measurements of plane albedo (line) performed in Antarctica (Dome C, 75°5' S, 123°17' E) for pure snow. The parameters *l*, *f*, *m* have been derived from the measurements at 400, 560, and 1020nm.

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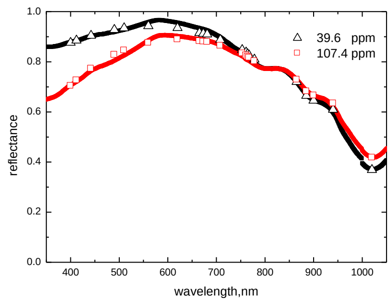

Fig.4 The inter-comparison of theory (symbols) with experimental measurements (line) in European Alps (45°55'56.70"N; 45°55'56.70"N) for the polluted snowpack. The parameters R_0, *l*, *f*, *m* have been derived from the measurements at 400, 560, 865 and 1020nm. Reflectance measurements were collected on snow containing different concentration of dust: 39.6 ppm (black line) and 107.4 ppm (red line). A complete description of this dataset is presented in Di Mauro et al. (2015).