Videocorrection of the images of the underlying surface with use of the reference channel in the UV-spectrum region

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Abstract – The mathematical model of spectral radiant intensity of the atmospheric haze without essential restrictions on the optical parameters of atmosphere is offered. The model is based on the solution of the radiative transfer equation for the difference between the exact solution and the solution in a small angle approximation (SAA). As SAA contains all the singularities of the exact solution, the indicated difference is a smooth function and its finding does not present difficulties by any numerical method of the solution. On the basis of the designed model the algorithm of videocorrection of the underlying surface images, founded on the definition of the atmosphere parameters by a signal in the reference channel in UV-spectrum region is offered.

Keywords: remote sensing, UV-spectrum region, radiative transfer equation.

1. INTRODUCTION

At the optical remote sensing the image of the underlying surface is strongly distorted by the influence of the light scattering in the atmosphere. In the UV-spectrum region the surfaces of practically all the ground objects have a low reflection factor, and the light scattering in the atmosphere essentially increases. It allows to allocate the channel in the UV-spectrum region, in which the signal is determined only by the radiance of an atmospheric haze. The existing methods of calculation of the atmospheric haze radiance are developed at the strong restrictions on the atmosphere parameters, particularly on the degree of the light scattering anisotropy. Such approach strongly restricts calculation opportunities in a broad spectral range.

It is connected with the features of a physical model of the radiation transfer – ray approximation. In particular, owing to the physically selected direction of the radiation propagation in space the radiance angular distribution contains a singularity. The singularity in the radiance angular distribution is internally proper to the description of the radiation transfer processes in the ray approximation, which essentially reduces convergence of the solution of the radiation transfer equation (RTE) by any numerical method.

This singularity of the radiance angular distribution is of the key character that requires the development of special methods of the RTE solution. Chandrasekhar, 1950, offered to subtract the direct nonscattered component from the solution and to state the equation for the smooth remainder that eliminates δ-singularity of the radiance angular distribution.

However the atmosphere has suspended particles with the size much greater then the wave length, that according to the Mie theory gives a strong anisotropic light scattering on them. In the conditions of a strong scattering anisotropy in the small angles the radiation is indistinguishable from the direct radiation, and the method of (Chandrasekhar, 1950) becomes ineffective.

The method of the elimination of this solution singularity is offered in the paper. It is based on the representation of the solution as the sum of the small angle approximation (SAA) and a smooth part. As SAA contains all the singularities of the exact solution, the indicated difference is a smooth function and its finding does not present difficulties by any numerical method of the solution.

On the basis of the designed model the algorithm of videocorrection of the underlying surface images, founded on the definition of the atmospheric parameters by a signal in the reference channel in UV-spectrum region is offered. The obtained values of the optical parameters of the atmosphere are recalculated in the primary channel in a visual or IR spectrum region. Using the mathematical model the radiance of the atmospheric haze and point distortion function in the primary channel are calculated, that allows making an image restoration of the underlying surface. As some materials (snow, limestone) have high value of reflectivity, the images in the reference channel can be a source of the completely new information about the state of the underlying surface.

2. METHOD OF RTE SOLUTION

Let's consider a boundary-value problem of RTE for an atmospheric slab irradiated from above by a flat unidirectional source

$$\begin{cases} \mu \dfrac{\partial L(\tau,\hat{\mathbf{l}})}{\partial \tau} + L(\tau,\hat{\mathbf{l}}) = \dfrac{\Lambda}{4\pi}\oint x(\hat{\mathbf{l}},\hat{\mathbf{l}}')L(\tau,\hat{\mathbf{l}}')d\hat{\mathbf{l}}', \\ L(\tau,\hat{\mathbf{l}})\Big|_{\tau=0,\mu\ge 0} = \delta(\hat{\mathbf{l}}-\hat{\mathbf{l}}_0),\;\; L(\tau,\hat{\mathbf{l}})\Big|_{\tau=\tau_0,\mu\le 0} = 0; \end{cases} \qquad (1)$$

where $L(\tau,\hat{\mathbf{l}}) \equiv L(\tau,\mu,\varphi)$ – radiance of a light field in the direction $\hat{\mathbf{l}} = \left\{\sqrt{1-\mu^2}\cos\varphi, \sqrt{1-\mu^2}\sin\varphi, \mu\right\}$, $\mu = (\hat{\mathbf{l}},\hat{\mathbf{z}})$, on the optical depth $\tau = \int_0^z \varepsilon(\xi)d\xi$;

$\hat{\mathbf{l}}_0$ – the incident direction of the external radiation on the upper bound of the slab, $\mu_0 = (\hat{\mathbf{l}}_0,\hat{\mathbf{z}})$;

ε – attenuation coefficient,

Λ – single scattering albedo of the medium;

τ_0 – slab optical thickness.

The axis *OZ* of a Cartesian frame is located perpendicularly downwards the slab border. Hereinafter the unit vectors are marked by the symbol "^".

The boundary-value problem (1) completely corresponds to the case of the optical remote sensing of an underlying surface in daylight conditions. In the real atmosphere the light scattering phase function in the expansion on Legendre polynomials has some hundreds terms. In this case the solution of (1) by any numerical

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method becomes mathematically ill-conditioned. Using the spherical harmonics method the number of the equations in the set is equal to the quantity of the terms in the expansion of the phase function on Legendre polynomials. In the discrete ordinates method (DOM) a very small-sized grid on the sighting angles is required, that results in the instability of the equation set. In algorithms of Monte-Carlo methods the backscattering is improbable event, which enters the solution with great weight. For the elimination of such instability we'll subtract from the solution an anisotropic angle part expressed by the solution of the RTE boundary-value problem (1) in SAA (Goudsmit, 1940):

$$L_{SAA}(\tau,\mu,\varphi)=\sum_{l=0}^{\infty}\sum_{n=-l}^{l}\frac{2l+1}{4\pi}Z_k(\tau)\,\mathrm{Q}_k^m(\mu_0)\,\mathrm{Q}_l^n(\mu)\,\mathrm{e}^{in\varphi}\,, \qquad (2)$$

where $\mathrm{Q}_l^n(\mu)=\sqrt{\frac{(l-n)!}{(l+n)!}}\mathrm{P}_l^n(\mu)$, $\mathrm{P}_l^n(\mu)$ – renormalized and associated Legendre polynomials accordingly;

$Z_k(\tau)=\exp\left\{-\frac{(1-\Lambda x_k)\tau}{\mu_0}\right\}$.

Let's present the solution of a boundary-value problem (1) as

$$L(\tau,\mu,\varphi)=L_{SAA}(\tau,\hat{\mathbf{l}},\hat{\mathbf{l}}_0)+\tilde{L}(\tau,\mu,\varphi)\,. \qquad (3)$$

The solution in SAA satisfies a similar boundary-value problem (1), but with boundary conditions neglecting a backscattering:

$$L_{SA}(\tau,\hat{\mathbf{l}},\hat{\mathbf{l}}_0)\Big|_{\tau=0}=\delta(\hat{\mathbf{l}}-\hat{\mathbf{l}}_0)\,. \qquad (4)$$

As SAA contains all the singularities of the exact solution of the problem (1), the rest $\tilde{L}(\tau,\mu,\varphi)$, satisfying a boundary-value problem

$$\begin{cases}\mu\dfrac{d\tilde{L}(\tau,\mu,\varphi)}{d\tau}=-\tilde{L}+\dfrac{\Lambda}{4\pi}\oint x(\hat{\mathbf{l}},\hat{\mathbf{l}}')\tilde{L}(\tau,\mu',\varphi')d\hat{\mathbf{l}}'+F(\tau,\mu,\varphi),\\ \tilde{L}(\tau,\mu,\varphi)\Big|_{\tau=0,\,\mu\ge 0}=0,\quad \tilde{L}(\tau,\mu,\varphi)\Big|_{\tau=\tau_0,\,\mu\le 0}=-L_{SA}(\tau_0,\mu,\varphi);\end{cases} \qquad (5)$$

where

$$F(\tau,\mu,\varphi)=-\mu\frac{dL_{SAA}(\tau,\mu,\varphi)}{d\tau}-L_{SAA}(\tau,\mu,\varphi)+\frac{\Lambda}{4\pi}\oint x(\hat{\mathbf{l}},\hat{\mathbf{l}}')L_{SAA}(\tau,\mu',\varphi')d\hat{\mathbf{l}}', \qquad (6)$$

is a smooth function at any degree of the scattering anisotropy. It eliminates the mathematical incorrectness of the problem (1) and allows using any numerical method for the solution (5). In the paper (Boudak, 2003) the determination algorithm of a smooth part of the solution by a method of spherical harmonics was considered, however analytical complexities in this case impede the generalization of the method on the case of the arbitrary medium geometry. Let's take the advantage of DOM for the solution (5), which allows extending an offered method to the case of three-dimensional medium geometry. The expression for the function $F(\tau,\mu,\varphi)$ is easy to calculate, using (2) and the addition theorem for the surface harmonic:

$$\begin{aligned}F_k^m(\tau)=\frac{\mu_0^{-1}}{2k+1}\Big[&\sqrt{(k-m+1)(k+m+1)}(1-\Lambda x_{k+1})\mathrm{Q}_{k+1}^m(\mu_0)Z_{k+1}\\&+\sqrt{(k-m)(k+m)}(1-\Lambda x_{k-1})\mathrm{Q}_{k-1}^m(\mu_0)Z_{k-1}(\tau)\Big]\\&-(1-\Lambda x_k)\mathrm{Q}_k^m(\mu_0)Z_k(\tau).\end{aligned} \qquad (7)$$

Let's present the scattering phase function as decomposition on Legendre polynomials, and the required function to a Fourier series on the azimuth

$$x(\cos\gamma)=\sum_{l=0}^{N}(2l+1)x_l\,\mathrm{P}_l(\cos\gamma)\,, \qquad (8)$$

$$\tilde{L}(\tau,\mu,\varphi)=\sum_{m=-\infty}^{\infty}C^m(\tau,\mu)\,\mathrm{e}^{im\varphi}\,, \qquad (9)$$

that after substitution in (5) taking into account the orthogonality of the azimuth harmonics will result in the combined equation set

$$\begin{aligned}\mu\frac{dC^m(\tau,\mu)}{d\tau}=&-C^m(\tau,\mu)+\sum_{k=0}^{\infty}\frac{2k+1}{4\pi}F_k^m(\tau)\mathrm{Q}_k^m(\mu)\\&+\frac{\Lambda}{2}\sum_{k=m}^{N}(2k+1)x_k\,\mathrm{Q}_k^m(\mu)\int_{-1}^{1}\mathrm{Q}_k^m(\mu')C^m(\tau,\mu')d\mu'.\end{aligned} \qquad (10)$$

Let's replace the integral in the equation (10) by a Gaussian quadrature

$$\int_{-1}^{1}\mathrm{Q}_k^m(\mu')C^m(\tau,\mu')d\mu'\approx\sum_{j=1}^{N}w_jC_j^m(\tau)\mathrm{Q}_k^m(\mu_j)\,, \qquad (11)$$

where w_i – weight coefficients of a Gaussian quadrature,
μ_j – roots of the polynomial $\mathrm{P}_{N+1}(\mu)$.

In this case the set (10) can be exchanged to the set of the N ordinary differential equations

$$\frac{d}{d\tau}\vec{\mathrm{C}}=-\vec{\vec{\mathrm{B}}}\vec{\mathrm{C}}+\vec{\mathrm{F}}(\tau)\,, \qquad (12)$$

where the following matrices and vectors are defined

$$\vec{\vec{\mathrm{m}}}=\mathrm{Diag}(\mu_i),\quad \left\{\vec{\vec{\mathrm{S}}}\right\}_{ji}=\frac{1}{2}\sum_{k=m}^{N}(2k+1)x_k\,\mathrm{Q}_k^m(\mu_i)\mathrm{Q}_k^m(\mu_j),$$

$$\vec{\mathrm{C}}=\left\{C_i^m\right\},\quad \left\{\vec{\mathrm{F}}(\tau)\right\}_i=\sum_{k=m}^{N}\frac{2k+1}{4\pi\mu_i}F_k^m(\tau)\mathrm{Q}_k^m(\mu_i),$$

$$\overleftrightarrow{\mathrm{B}} = \overleftrightarrow{\mathrm{m}}^{-1}(\overleftrightarrow{1} - \Lambda \overleftrightarrow{\mathrm{S}}\overleftrightarrow{\mathrm{W}}), \quad \overleftrightarrow{\mathrm{W}} = \mathrm{Diag}(w_i).$$

The set solution looks like

$$-\vec{\mathrm{C}}(0) + \overleftrightarrow{\mathrm{U}}\, \mathrm{e}^{\overleftrightarrow{\Gamma}\tau_0} \overleftrightarrow{\mathrm{U}}^{-1} \vec{\mathrm{C}}(\tau_0) = \overleftrightarrow{\mathrm{U}} \int_0^{\tau_0} \mathrm{e}^{\overleftrightarrow{\Gamma}t} \overleftrightarrow{\mathrm{U}}^{-1} \vec{\mathrm{F}}(t)dt \;, \tag{13}$$

where $\quad \mathrm{e}^{\overleftrightarrow{\mathrm{B}}\tau} = \overleftrightarrow{\mathrm{U}}\mathrm{e}^{\overleftrightarrow{\Gamma}\tau}\overleftrightarrow{\mathrm{U}}^{-1}$.
The free term in (13) is expressed as

$$\begin{aligned} &\int_0^{\tau_0} \mathrm{e}^{\overleftrightarrow{\Gamma}t} \overleftrightarrow{\mathrm{U}}^{-1} \vec{\mathrm{F}}(t)dt = \\ &= \frac{1}{4\pi} \sum_{k=0}^{N} \left[\frac{k+1}{\mu_0} \overleftrightarrow{\mathrm{j}}_{k+1} + \frac{k}{\mu_0} \overleftrightarrow{\mathrm{j}}_{k-1} - (2k+1)\, \overleftrightarrow{\mathrm{j}}_k \right] \overleftrightarrow{\mathrm{U}}^{-1} \overleftrightarrow{\mathrm{m}}^{-1} \vec{\mathrm{Q}}_k^m, \end{aligned} \tag{14}$$

where $\quad \overleftrightarrow{\mathrm{j}}_k = d_k \left(\frac{d_k}{\mu_0} \overleftrightarrow{1} - \overleftrightarrow{\Gamma} \right)^{-1} \left[\overleftrightarrow{1} - \exp\left[-\left(\frac{d_k}{\mu_0} \overleftrightarrow{1} - \overleftrightarrow{\Gamma} \right) \tau_0 \right] \right] \mathrm{Q}_0,$

$$d_k = (1 - \Lambda x_k), \quad \vec{\mathrm{Q}}_k^m = \left\{ \mathrm{Q}_k^m(\mu_i) \right\}, \quad \mathrm{Q}_0 = \mathrm{Q}_k^m(\mu_0).$$

The condition of the system matrix (13) is quickly worsened with the increase of the slab depth. For the elimination of this effect it is necessary to take advantage of the scale transformation (Karp, 1980) and to multiple both parts (13) by a matrix $\overleftrightarrow{\mathrm{S}}\overleftrightarrow{\mathrm{U}}^{-1}$. Therefore the equation (13) will accept the form

$$\begin{aligned} &-\overleftrightarrow{\mathrm{S}}\,\overleftrightarrow{\mathrm{U}}^{-1} \vec{\mathrm{C}}(0) + \overleftrightarrow{\mathrm{H}}\,\overleftrightarrow{\mathrm{U}}^{-1} \vec{\mathrm{C}}(\tau_0) = \\ &\quad = \sum_{k=0}^{N} \left[\frac{k+1}{\mu_0} \overleftrightarrow{\mathrm{S}\mathrm{j}}_{k+1} + \frac{k}{\mu_0} \overleftrightarrow{\mathrm{S}\mathrm{j}}_{k-1} - (2k+1) \overleftrightarrow{\mathrm{S}\mathrm{j}}_k \right] \overleftrightarrow{\mathrm{U}}^{-1} \overleftrightarrow{\mathrm{m}}^{-1} \vec{\mathrm{Q}}_k, \end{aligned} \tag{15}$$

where $\quad \overleftrightarrow{\mathrm{S}} = \begin{bmatrix} 0 & \mathrm{e}^{-\overleftrightarrow{\Gamma}_+\tau_0} \\ \overleftrightarrow{1} & 0 \end{bmatrix}, \quad \overleftrightarrow{\mathrm{H}} = \begin{bmatrix} 0 & \overleftrightarrow{1} \\ \mathrm{e}^{\overleftrightarrow{\Gamma}_-\tau_0} & 0 \end{bmatrix}, \quad \overleftrightarrow{\Gamma} = \begin{bmatrix} \overleftrightarrow{\Gamma}_- & 0 \\ 0 & \overleftrightarrow{\Gamma}_+ \end{bmatrix},$

$$\overleftrightarrow{\Gamma}_+ = -\overleftrightarrow{\Gamma}_- = \mathrm{Diag}\{\gamma_i\}, \;\; \gamma_i < \gamma_{i+1},$$

$$\overleftrightarrow{\mathrm{S}\mathrm{j}}_k = d_k \left(\frac{d_k}{\mu_0} \overleftrightarrow{1} - \overleftrightarrow{\Gamma} \right)^{-1} \begin{bmatrix} \overleftrightarrow{0} & \mathrm{e}^{-\overleftrightarrow{\Gamma}_+\tau_0} - \overleftrightarrow{1}\mathrm{e}^{-d_k\tau_0/\mu_0} \\ \overleftrightarrow{1} - \mathrm{e}^{\left(\overleftrightarrow{\Gamma}_- - \overleftrightarrow{1} d_k/\mu_0\right)\tau_0} & \overleftrightarrow{0} \end{bmatrix} \mathrm{Q}_0 \,.$$

The set (15) contains the N equations with the $2N$ unknown quantities. The boundary conditions give the missing N equations

$$C^m(0,\mu_i)\Big|_{\forall i:\,\mu_i \ge 0} = 0, \quad C^m(\tau_0,\mu_i)\Big|_{\forall i:\,\mu_i \le 0} = -L_{SAA}(\tau_0,\mu_i)\,, \tag{16}$$

which can give a matrix form too.

The offered algorithm differs by rapid convergence: N>20 is enough for Henyey-Greenstein scattering phase function $x_k=g^k$ with parameter g=0.9. The generalization of the indicated algorithm on the case of the arbitrary three-dimensional geometry does not represent any difficulties. Such approach is similar to SHDOM (Evans, 1993), however it exceeds essentially on the convergence due to the analytical registration of the angular singularities of the solution.
The registration of the diffuse reflection from the underlying surface completely corresponds to regular DOM. For the solution of a boundary-value problem (1) in the inhomogeneous medium the slab is divided into the set of homogeneous slabs. The requirement of the coefficient continuity (9) is established on borders between them. The rapid convergence of the algorithm practically doesn't limit the amount of the slabs in the mathematical model.

3. RESULTS OF COMPUTATIONAL MODELING

At the calculation of the signals in the system of the optical remote sensing of the underlying surface the model of the optical performances from (Mc Clatchey, 1977), and spectral dependences of a reflectance of the underlying surface from (Eaton, 1979) were taken.
In Fig. 1-3 the calculations results of the light field parameters are given for the following conditions: a solar angle is 50°, observation is in the nadir, meteorological visibility range on the Earth surface is 20 km, the underlying surface is vegetation or fresh snow, short-wave limit of the observation range is 0.3 microns. The calculations were performed for various observation heights h, where the maximum observation height of 650 km is adopted as a typical flight height of the satellites of the remote sensing of the natural resources.
The most visually the relation between a haze and a signal is represented by the spectral dependence of the coefficient κ (Fig. 1), which is the ratio of the haze radiance to the object radiance. The coefficient κ characterizes the degree of the contrast decreasing because of the atmosphere influence. One can see from Fig. 1, that in the spectrum range about 0.3 microns the haze radiance completely predominates above the signal, that allows to recommend this spectrum range for the reference channel on the haze radiance measurement. The necessary optical parameters of the atmosphere can be determined from extra scanning of the atmosphere in the height. Such algorithm is equivalent to the differential algorithm of the compensation of the backscattering radiance offered in (Gordon, 1978).
The UV - channel can be used not only as the reference in the system of videocorrection, but also for the direct sensing of the underlying surface. For the comparison in Fig. 2 the diagrams of κ for snow are given. It is easy to see, that there are other contrasts in UV - range which are not apparent in a visible band that makes it possible to use it effectively at the remote sensing, for example, for the observation of snow and ice covers.
However the low value of signals and contrasts in comparison with a visible band show the strict requirements to the contrast sensitivity of TV-system. The opportunity of the image processing with the purpose of the contrast range magnification and the corrections of the spatially - frequency distortion are determined by the signal/noise ratio ψ.In the practice of the remote sensing the high-performance TV - system with optical-mechanical scan and single-element receiver on the photomultiplier tube found the broad application. In Fig. 3 the relative spectral dependence $\psi_\lambda / \psi_{0.55}$ is shown for such systems, which are calculated at the constant device parameters. From the analysis of the given de-

pendence it is obvious, that the TV-systems in UV - spectrum (in comparison with the visible band) at the equal requirements to the resolving ability and ψ demand increasing sensitivity in more than 100 times.

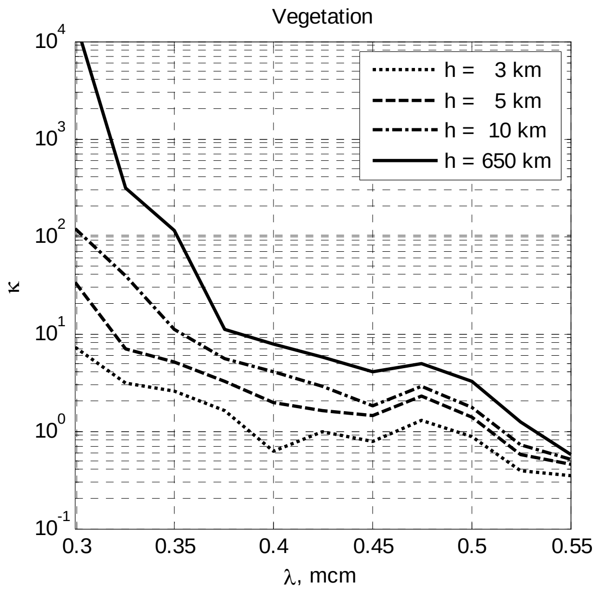

Figure 1. The ratio of the haze radiance to the object radiance

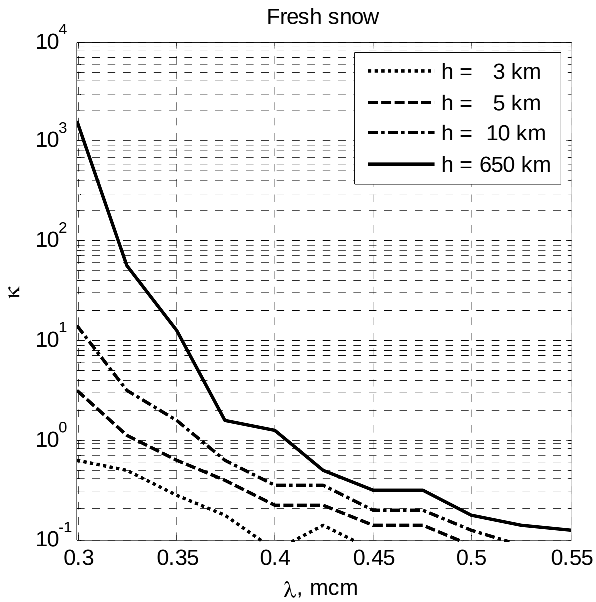

Figure 2. The ratio of the haze radiance to the object radiance

Therefore, owing to the dominant contribution of the atmosphere in the signal the operation of TV-system takes place in the mode of the background restriction that determinates low contrasts and signal / noise ratio of the UV images.

4. CONCLUSIONS

The simulation of the observation conditions in UV-range shows a key opportunity of its usage as the reference channel for the definition of the backscattering radiance. On the other hand, unusual contrasts of natural formations in UV allow recommending it for the purposes of sensing on a snow cover.

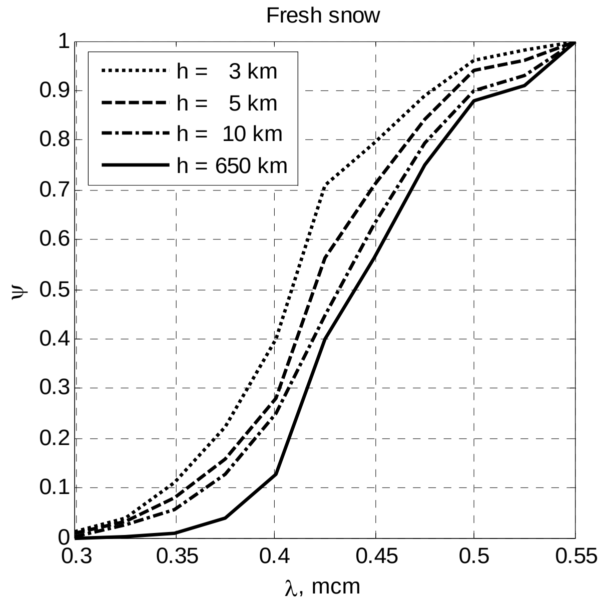

Figure 3. The relative signal to noise ratio

5. REFERENCES

Boudak V.P., Kozelsky A.V., Savitsky E.N. “Mathematical model of solar radiation reflection by underlying surface,” Proc. SPIE, vol.5396, p.p.221-227, 2003.

Chandrasekhar S. “Radiative Transfer,” Clarendon Press, Oxford, 1950.

Goudsmit S., Saunderson J.L. “Multiple scattering of electrons,” *Phys.Rev.*, vol.57, pp.24-29, 1940.

Eaton F.D., Dirmhirn V.I. “Reflected irradiance indicatrices of natural surface and their effect on albedo,” App. Opt., vol.18, N7, p.p.994-1008, 1979.

Evans K.F. “Two-dimensional radiative transfer in cloudy atmospheres: The spherical harmonic spatial grid method,” J. Atmos. Sci., vol.50, p.p.3111–3124, 1993:

Karp A.H., Greenstadt J., Fillmore J.A. “Radiative transfer through an arbitrary thick, scattering atmosphere,” J. Quant. Spectr. Rad. Trans., vol.24, p/p.391-406, 1980.

Mc Clatchey R.F., Bolle J., Kondratyev K.Ya. a.o. “Report of the IAMAP Radiation Commission Working Group on a Standard Radiation Atmosphere,“ Seatle, Washington. USA. 29 August, 1977.

Gordon H.R. “Removal of atmospheric effect from satellite imagery of the ocean,” Appl. Opt., 1978, N10, p.p.1631-1635.