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Review paper I Прегледни научни рад
DOI 10.7251/STP2215487M
ISSN 2566-4484

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INFLUENCE OF MATERIAL SURFACE ROUGHNESS ON BACKSCATTERING IN LASER SCANNING

Abstract

In this paper, the possibility of applying Kirchhoff 's scalar approximation model for determining the backscattering coefficient from rough surfaces is investigated. Surfaces of dielectric and metallic materials, which have low roughness are considered. Based on the roughness parameters and electrical properties of these materials, the backscattering coefficient is modelled as a function of the incident angle of electromagnetic radiation used in laser scanning. It was represented that the type of scattering and the range of backscattering radiation angles, in the case of seemingly smooth surfaces, vary significantly when the roughness parameters change.

Keywords: Kirchhoff's scalar approximation model, Roughness parameters, Laser scanning, Backscattering coefficient.

УТИЦАЈ ХРАПАВОСТИ ПОВРШИНЕ МАТЕРИЈАЛА НА ПОВРАТНО ЗРАЧЕЊЕ КОД ЛАСЕРСКОГ СКЕНИРАЊА

Сажетак

У овом раду испитивана је могућност примене Кирхофовог модела скаларне апроксимације за одређивање коефицијента повратног расејања од храпавих површина. Разматране су површине диелектричних и металних материјала које имају малу храпавост. На основу параметара храпавости и електричних особина тих материјала, моделиран је коефицијент повратног расејања у зависност од упадног угла електромагнетског зрачења које се користи код ласерског скенирања. Показано је да тип расејања и опсег углова повратног расејања, код привидно глатких површина, вишеструко варирају при промени параметара храпавости.

Кључне ријечи: Кирхофов модел скаларне апроксимације, Параметри храпавости, Ласерско скенирање, Коефицијент повратног расејања.

1. INTRODUCTION

Many measurement methods in geodesy are based on measuring the characteristics of reflected electromagnetic (EM) waves from an object or a surface. The intensity and direction of the reflected radiation are influenced by the characteristics and direction of the incident radiation, the electrical and magnetic properties of the material, and the geometric characteristics of the reflecting surface. Knowledge of the physical principles on which the reflection of EM radiation from different types of surfaces is based as well as its influence on the measurement signal, enables prediction of measurement errors, and allows the use of these measurement systems to identify different types of surfaces [1,2].

Terrestrial laser scanner (TLS) provides accurate, high-resolution data by measuring the distance between scanned points and the scanner center using time-of-flight or phase-shift-based methods. Distance measurement accuracy in TLS depends on the instrument mechanism, atmospheric conditions, scanning geometry, and target surface properties [13].

In active laser systems, the reflection of waves from real surfaces which are generally rough is used. If the surfaces under consideration are highly reflective, whose specular reflections are dominant, significant errors (centimeter and even decimeter levels) may occur, because these reflections can increase the backscattered laser signal power considerably and cause further disturbance in echo detection and recognition by TLS photodetectors [13].

The application of lasers is based on the directivity and modulation of the laser beam, and on the reception and processing of reflected laser radiation from the surface of the object. In applications based on the reception and processing of reflected laser radiation, information is contained in the change of amplitude, phase and frequency of the reflected signal. The phase change and return time of the reflected signal is used to measure the distance from the object. The distribution of the intensity of reflected radiation, as a function of incident and reflected angles, depends on the properties of the tested material (roughness and electrical and magnetic properties), the properties of electromagnetic radiation (wavelength and polarization). There are different models for calculating and analyzing the intensity of reflected EM waves from the surface of the object and these models depend on the parameters of material roughness and the properties of laser radiation. There is no single model for calculating the reflection from rough surfaces and for all models there are some boundary conditions of use because they are all based on some kind of approximation.

Intensity-based method for correcting distance measurement errors from the center of the scanner to the object is presented in [13], where distance and intensity data are directly derived from the characteristics of backscattered signals. Roughness of the surface is one of the main features for modeling distance errors.

This paper describes the scattering (reflection) of radiation from rough surfaces and applies Kirchhoff's model of scalar approximation to several surfaces of different materials and different roughness parameters. Kirchhoff 's model presents a rough surface as randomly oriented small mirrors that touch the surface [3]. For these mirrors, depending on their orientation in space and the type of material, Fresnel reflection coefficients are obtained for parallel and perpendicular polarized incident electromagnetic waves [3-5]. The paper explains the criteria for determining whether a surface is rough and the parameters that more closely describe the surface roughness as well as the range of parameter values for which Kirchhoff's scalar approximation model is applied. In laser scanning, in addition to the material properties of the surface to be scanned, the intensity of the backscattered radiation depends on the incidence angle. For surfaces that are slightly rough and seemingly smooth, such as dielectrics (glass and plastic) and metals (copper and iron), the angular distribution of backscattered radiation has been determined as a function of the incident angle.

2. THEORY

2.1. REFLECTION OF ELECTROMAGNETIC WAVES FROM FLAT SURFACES

EM waves represent the transmission of oscillations of electric and magnetic fields through space. For laser scanning applications, plane EM waves are generally considered. The electric and magnetic fields are normal to each other and normal to the direction of propagation of these waves. Electromagnetic waves for many applications can be represented by its electric field vector $\vec{E}$. When a plane EM wave incidents on a flat boundary surface between two homogeneous media (1 and 2), whose refractive indices are n_1 and n_2 it is partially refracted and partially reflected (Figure 1). The direction of the incident EM wave and the normal to the surface make the incident angle θ_1. The part of the ray wave is reflected back to the media 1 at the same angle θ_1, and the part is refracted and passes to the medium 2. The direction of the refractive wave makes the angle θ_2 with the normal to the boundary surface. The incident, reflected and refractive rays and the normal to the boundary surface lie in the same plane called the incident or incident plane. The incident EM wave is usually represented as the sum of two linearly polarized waves, the first whose electric field vector $\overrightarrow{E_{par}}$ is parallel to the incident plane and the second whose electric field vector $\overrightarrow{E_{perp}}$ is normal to the incident plane, so the incident wave vector is represented as $\vec{E}=\overrightarrow{E_{par}}+\overrightarrow{E_{perp}}$. In order to represent the intensity of the reflected wave vector $\vec{E'}$, the reflection coefficient *r* is determined, which represents the ratio of the intensity of the electric field vector of the reflected and incident waves. Due to the representation of the incident wave over the mutually normal two polarized waves, this coefficient is determined for each polarization separately. The reflected wave can be represented as $\overrightarrow{E'_{par}}$ and $\overrightarrow{E'_{perp}}$, so two reflection coefficients r_{par} and r_{perp} are determined. Reflection coefficients can be determined using the laws of refraction and reflection of waves and boundary conditions that connect their electric and magnetic field vectors at the boundary surface, as well as knowledge of dielectric constants of materials ε_1 and ε_2 and their magnetic permeabilities μ_1 and μ_2. They are called Fresnel coefficients.

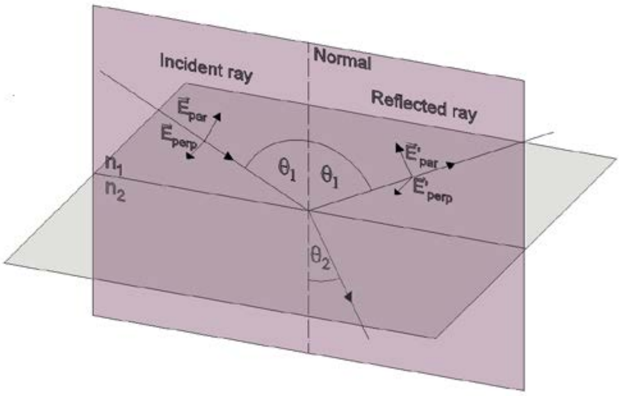

Figure 1. *Reflection and refraction of EM waves from a flat boundary surface*

Fresnel reflection coefficients, in the general case, for media that have pronounced electrical and magnetic properties can be determined from the expressions [3]:

$$r_{perp}=\frac{Z_2\cos\theta_1-Z_1\cos\theta_2}{Z_2\cos\theta_1+Z_1\cos\theta_2}, \quad (1)$$

$$r_{par}=\frac{Z_2\cos\theta_2-Z_1\cos\theta_1}{Z_2\cos\theta_2+Z_1\cos\theta_1}. \quad (2)$$

In these expressions $Z_1=\sqrt{\frac{\mu_1}{\varepsilon_1}}$ and $Z_2=\sqrt{\frac{\mu_2}{\varepsilon_2}}$ represent the characteristic impedances of the media. However, in practice majority of the materials do not have pronounced magnetic properties and their magnetic permeability $\mu\approx 1$. In addition, it is assumed that the medium 1 from which the incident wave comes is air, whose characteristic impedance is $Z_1=\sqrt{\frac{1}{\varepsilon_0}}$, and the medium 2, in the general case, is the absorbing medium of the relative dielectric constant ε_{r2}. In this case, the Fresnel reflection coefficients are represented by the expressions:

$$r_{perp}=\frac{\cos\theta_1-\sqrt{\varepsilon_{r2}-\sin^2\theta_1}}{\cos\theta_1+\sqrt{\varepsilon_{r2}-\sin^2\theta_1}}, \quad (3)$$

$$r_{par}=\frac{\sqrt{\varepsilon_{r2}-\sin^2\theta_1}-\varepsilon_{r2}\cos\theta_1}{\sqrt{\varepsilon_{r2}-\sin^2\theta_1}+\varepsilon_{r2}\cos\theta_1}. \quad (4)$$

If the medium 2 is absorptive, a complex number is used to represent its relative dielectric constants ε_{r2}. The most common way of presentation complex relative dielectric constants is:

$$\varepsilon_{r2}=\varepsilon_2'-i\varepsilon_2'', \quad (5)$$

where $i^2=-1$, $\varepsilon_2^{'}$ is the real part of the relative dielectric constant, and $\varepsilon_2^{''}$ is the imaginary part of the relative dielectric constant. The refractive index of the same energy-absorbing material is represented by a complex number as follows:

$$n_2=m_2-ik_2, \quad (6)$$

where m_2 and k_2 are the real and imaginary part of the refractive index. Complex index of refraction and complex relative dielectric constant and their real and imaginary parts are connected based on the expression:

$$n_2=\sqrt{\varepsilon_{r2}}. \quad (7)$$

In case the material does not absorb energy from EM wave its the relative dielectric constant ε_{r2} and index of refraction n_2 are real numbers. As the medium 1 has a refractive index $n_1 = 1$, the reflection coefficients in this case can be derived from:

$$r_{perp}=\frac{\cos\theta_1-\sqrt{n_2^2-\sin^2\theta_1}}{\cos\theta_1+\sqrt{n_2^2-\sin^2\theta_1}}, \quad (8)$$

$$r_{par}=\frac{\sqrt{n_2^2-\sin^2\theta_1}-n_2^2\cos\theta_1}{\sqrt{n_2^2-\sin^2\theta_1}+n_2^2\cos\theta_1}. \quad (9)$$

2.2. REFLECTION OF ELECTROMAGNETIC WAVES FROM ROUGH SURFACES

Roughness is a measure of statistical variation in the distribution of topographic surface relief. [8] For rough materials, the surface level changes, and can be represented by a two-dimensional function *z(x, y)*, in the general case.

For simplicity of presentation and development of basic models, rough surfaces are observed along one direction *x*, and its height is represented as *z(x)*. The mean height $\langle z\rangle$ for all values of *x* in the observed range is determined. A large number of parameters can be used to describe surface roughness, but two parameters are most commonly used on which the basic models of EM wave scattering from rough surfaces are based. The first parameter is the mean square variation of the height Δh which is the simplest measure of surface roughness (Figure 2). [3] And it is determined based on:

$$\Delta h=\sqrt{\sum(z(x)-\langle z\rangle)^2}, \quad (10)$$

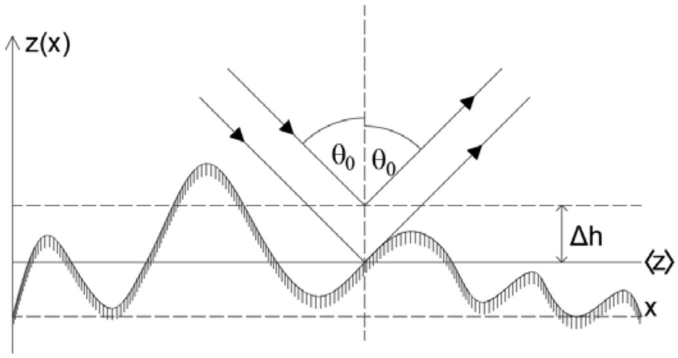

Figure 2. *Surface level presentation by function z(x) and parameter Δh*

However, this parameter only tells about the deviation of the surface height from the mean value, but it does not tell about the spatial periodicity of these changes, so it is necessary to determine the characteristic period of repetition of height oscillations along the *x*-axis. This is most often represented by an autocorrelation function defined as [10]:

$$\rho(\xi)=\frac{\sum(z(x+\xi)-\langle z\rangle)(z(x)-\langle z\rangle)}{\Delta h^2}, \quad (11)$$

and it is a measure of the similarity of height at two distant points along the x axis at a distance ξ.
By definition, the limit values of this quantity are $\rho(0)=1$, and most often $\rho(\infty)=0$.
The most commonly used models for this autocorrelation function are:

- Gaussian distribution

$$\rho(\xi)=e^{-\frac{\xi^2}{L^2}} \quad (12)$$

- or negatively exponential distribution

$$\rho(\xi)=e^{-\frac{|\xi|}{L}}. \quad (13)$$

In both cases, the quantity *L* is a measure of the width of the irregularity on the surface and is called the correlation length.

In addition to the basic parameters that most often describe the surface roughness, there are other parameters that in combination with the previously mentioned parameters even better describe the given surface. Some of these parameters are Skewness (*Sk*), Peak to valley height (*PVh*) and Root mean square slope (RMS slope). Skewness is a measure which describes a degree of asymmetry from the normal distribution of surface heights. This parameter is using very often in a combination with the standard deviation or other indices that assume the normal distribution of surface heights. The index can be calculated by:

$$S_k=\frac{\frac{1}{N}\sum_1^N (z(x_i)-\langle z\rangle)^3}{\left(\frac{1}{N}\sum_1^N (z(x_i)-\langle z\rangle)^2\right)^{3/2}} \quad (14)$$

A Peak to valley height is a statistical measure which takes the two most extreme heights its maximum h_{max} and its minimum h_{min} of a surface. This index is used in surface metrology where surface roughness is considered as irregularities coming from a manufacturing process. This index can be calculated by the next formula:

$$PVh = h_{max} - h_{min}. \quad (15)$$

Root mean square slope represents the root mean square for the local slope dz/dx a long the sampling length,

$$RMS\,\text{slope} = \frac{1}{N}\sqrt{\sum_1^N \left(\left(\frac{dz(x)}{dx}\right)_{x=x_i}\right)^2}. \quad (16)$$

This parameter is in relation with *Δh* and *L* and in case of Gaussian distribution, the relation is RMS slope = $\sqrt{2}\frac{\Delta h}{L}$.

For ideally rough surfaces, it is often assumed that the height distribution is represented by the Gaussian distribution, because it is the result of a random process. It is also assumed that the correlation function most often has a Gaussian distribution, although sometimes the exponential correlation function corresponds better to the measured surface data [9].

2.3. SURFACE SCATTERING MODELING

Scattering (reflection) of radiation from different types of surfaces (smooth and rough) is one of the basic physical processes used to characterize the surface of the material. Based on the characteristics of the surface, the angle at which the scatter radiation is greatest can be determined. Therefore, the consideration of the reflection properties of real surfaces is of great importance. Simple surface scattering models describe two boundary surface types, an ideally smooth surface (mirror) and an ideally rough surface. If the surface that scatters radiation is smooth enough, it will act as a mirror, and such scattering is called specular reflection and will behave according to the law of reflection, ie. all incident radiation will be reflected at the same angle as the incident radiation. The second basic behavior occurs when the surface is ideally rough and is called Lambertian scattering. In this type of scattering, radiation that incidents at some angle and is uniform per unit area, is reflected in all directions, ie. the radiation is scattered at all angles isotropically as presented in Figure 3.

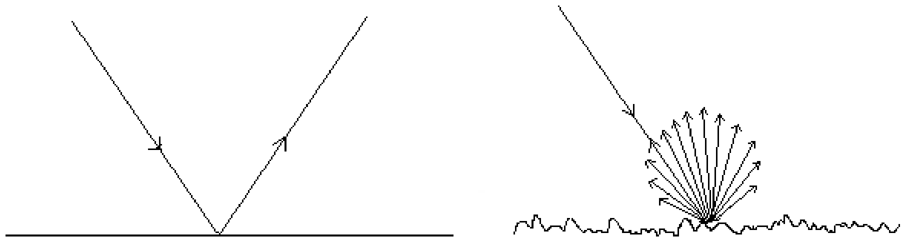

Figure 3. *Schematic representation of two boundary cases of surface scattering a) Specular reflection; b) Lambert scattering (Based on Fig.1 in [12])*

Therefore, scattering from rough surfaces cannot be represented only by Fresnel coefficients, but it is necessary to introduce other coefficients related to scattering.

The basic coefficient of scattered surface radiation is BRDF (*Bidirectional Reflection Distribution Function*) and it is a function of the directions of the incident and scattered radiation, so it can also be written as a function *R* of $(\theta_0,\phi_0,\theta_1,\phi_1)$. It represents the ratio of the irradiance L_1 of scattered radiation in the direction described by angles (θ_1,ϕ_1) to the unit spatial angle $d\Omega_1$ and the flux *F* of incident radiation from the direction represented by angles (θ_0,ϕ_0) to the surface *dA* (Figure 4). This presentation is useful because it emphasizes reciprocity in relation to the directions of incident and scattered radiation, ie.

$$R\left(\theta_0,\phi_0,\theta_1,\phi_1\right)=R\left(\theta_1,\phi_1,\theta_0,\phi_0\right). \tag{17}$$

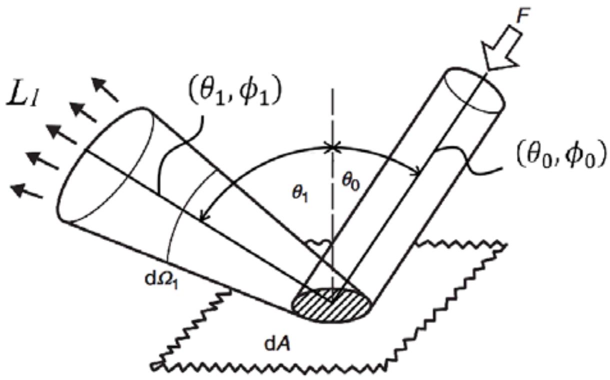

Figure 4. *Based on Fig. 3.9. [3] Quantities defining scattered radiation from a rough surface dA (azimuth angles ϕ_0 and ϕ_1 are not completely represented due to image clarity)*

Most laser systems detect only the radiation scattered backward, ie. which returns along the same path as the incident radiation. When $\theta_0 = \theta_1$ and $\phi^0 = \phi 1$, such backscattered radiation is most often represented by the dimensionless backscattering coefficient, σ^0 represented by the following expression:

$$\sigma^0=4\pi R\cos^2\theta_0. \tag{18}$$

There is no surfaces that are absolutely rough or smooth, but it depends on the wavelength of the incident electromagnetic radiation. Therefore, criteria are introduced based on which it can be approximately determined whether the surface can be considered rough or smooth, and one of the basic ones is the Rayleigh criterion. Figure 2 schematically shows the behavior of radiation that falls on a rough surface at an angle θ_0 and is reflected from it at the same angle. Observing two parallel rays falling on that surface, it is introduced that one is reflected from the reference plane whose height is equal to the middle level of the surface $\langle z\rangle$, and the other from the parallel plane which is at the height Δh above this reference plane. After scattering, the difference between the traversed paths of these two rays is $2\Delta h\cos\theta_0$, and their phase difference is:

$$\Delta\phi = \frac{4\pi\Delta h\cos\theta_0}{\lambda} \tag{19}$$

where λ is the wavelength of the radiation. As Δh denotes the mean square variation of the rough surface height, so $\Delta\phi$ represents the mean square variation of the scattered beam phase. The surface can be considered smooth enough for scattering to be specular if $\Delta\phi$ is less than some predefined value of order 1 rad. [3] The usual value is π/2 and it is characteristic of the Rayleigh criterion. Therefore, for scattering to be specular according to Rayleigh's criterion, Δh must satisfy the condition:

$$\Delta h <= \frac{\lambda}{8\cos\theta_0} \tag{20}$$

From this formula, we can see whether the surface is rough depends on the wavelength of the radiation and the angle of incidence. Based on Equation 17, it is shown that the surface is smooth enough for radiation falling normally on the surface if Δh is less than λ/8.

2.3.1.Kirchhoff's model of scalar approximation

In this paper, Kirchhoff's model is used to model scattering from rough surfaces. In this model, the randomly rough surface is represented by randomly oriented small mirrors that touch the surface [3]. In this way, scattered radiation is represented by reflected radiation from these small mirrors, so this model is also called tangent plane approximation [5,11].

The three basic assumptions for these model are [5]:

- Tangent plane hypothesis: at each point of the surface, the roughness is assumed to have the same optical behavior as its tangent plane. Fresnel laws can thus be locally applied;
- Fresnel reflection coefficients is independent on the position on the rough surface and on the local angle of incidence;
- Calculations are performed in the far-field.

There are two types of Kirchhoff's model and first one, the stationary phase model is based on the application of the laws of geometric optics and applies to rougher surfaces [3-5,11]. Second, the scalar approximation model is based on the laws of physical optics and is applied to slightly rough surfaces [6]. These surfaces are approximately smooth and there correlation length L is considered to be greater than the wavelength of the radiation, and the mean square value of the surface height Δh is small enough that the slopes of the mirrors are small.

The general equations describing scattering from rough surfaces according to Kirchhoff's model are presented in detail in [5] and [14]. Based on them, different types of scattering coefficient could be derived for various directions of incident and reflected radiation.

The backscattering coefficient for the scalar approximation model for the parallel polarization of the incident radiation is determined according to the expression [6]:

$$\sigma^0_{pp}(\theta)=k^2L^2\cos^2\theta\left|r_p(\theta)\right|^2 \exp\left(-4k^2\Delta h^2\cos^2\theta\right)\times\sum_{n=1}^{\infty}\frac{(2k\Delta h)^{2n}}{n!n}\exp\left(-4(k^2L^2\sin^2\theta)/n\right). \tag{21}$$

In this expression, it is assumed that the correlation length L is determined by the Gaussian autocorrelation function, $r_p(\theta)$ represents the Fresnel coefficient for parallel polarized radiation and the quantity $k = 2\pi / \lambda$ represents the wave number of incident radiation.

Kirchhoff's model of scalar approximation is valid for the following relations of parameters Δh, L and k [3]:

$$\Delta h<0.18\,L\,, \tag{22}$$

$$kL>6\,, \tag{23}$$

$$kL^2>17.3\,\Delta h. \tag{24}$$

In the Kirchhoff's model, care should be taken to choose appropriate size of the "mirrors", because they must be larger than a few wavelengths, in order to avoid the effect of radiation diffraction. Also, the angles of intrusion and scattering should not be too large, in order to prevent the shading of one part of the surface by another. This model also does not consider multiple scattering.

3. RESULTS AND DISCUSION

Within the MATLAB software package, programs for determining the Fresnel reflection coefficients and the backscattering coefficient of different materials have been created. These programs enable the calculation for different radiation wavelengths, as well as for different parameters of material surface roughness.

The most often radiation wavelengths λ used in laser scanning are 532 nm and 1064 nm [4], and calculations were performed for these two wavelengths. The considered range of incidence angles is from 0° to 70°. For two types of dielectric materials (glass and plastic) and metals (copper and iron), the parameters Δ*h* and *L* were varied to meet the conditions of expressions (22), (23) and (24). Based on them the dependence of the backscattering coefficient on the incident angle was determined.

For the calculation the backscattering coefficient based on Kirchhoff's scalar approximation model, the part of expression (21) representing the infinite sum *S* is especially considered. Therefore, the value of the n-th term of the sum for *n* = [0,10] was first calculated according to expression (25), and this is presented in Figure 7 as the dependence *S(n).* The calculation was performed for different incidence angles from 0º to 70º and it was noticed that the value of the members *S(n)* behaves in a similar way for all angles from the given range.

$$S(n) = \frac{(2k\Delta h)^{2n}}{n!n} \exp\left(-4(k^2L^2\sin^2\theta)/n\right). \quad (25)$$

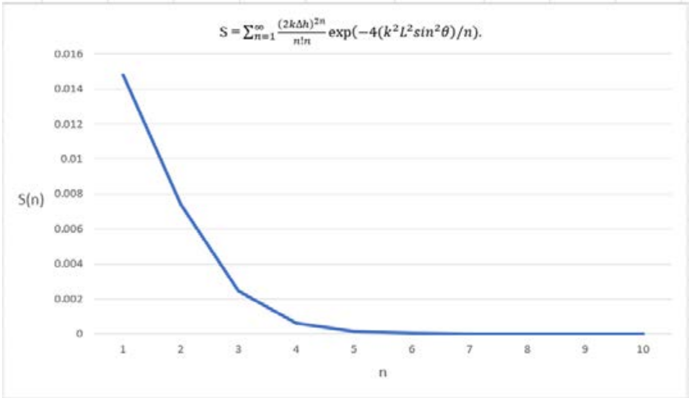

Figure 5. *Sum chart for members 1 to 10*

Based on the obtained results shown in the Figure 5, it is obvious that the influence of the members with *n* > 5 on the summation is negligible. So the sum in expression (21) is calculated based on the first 5 members. For all materials that are modeled, the adopted values for Δ*h* and *L* are shown in Table 1.

Table 1.Adopted values of roughness parameters Δh and L for wavelength 532 nm

Δh [μm]	L[μm]
0.02	0.8
0.04	1.6
0.12	4.8

The obtained results are shown only for the wavelength 532 nm, since the results of the wavelength 1064 nm do not differ significantly from them.

3.1. GLASS

The refractive index for glass is a real number and is 1.5261 for a wavelength 532 nm. Fresnel reflection coefficients were determined based on expressions (8) and (9) and presented as graph in Figure 6a). The values of the backscattering coefficient were calculated for two ways of varying the roughness parameters:

- at a constant value of *L* (1.6μm) for different values of Δ*h* (0.02μm, 0.04μm and 0.12μm) which is shown in Figure 6b),
- at a constant value of Δ*h* (0.04μm), and for different values of *L* (0.8μm, 1.6μm and 4.8μm), which is shown in Figure 6c).

On smooth surfaces the radiation is reflected backwards in a narrow range of angles, while on rough surfaces the backscattered radiation is distributed over large range of angles. As the value of Δ*h* increases, the surface becomes rougher, while as the value of *L* increases, the surface becomes smoother, which can be seen in the pictures below.

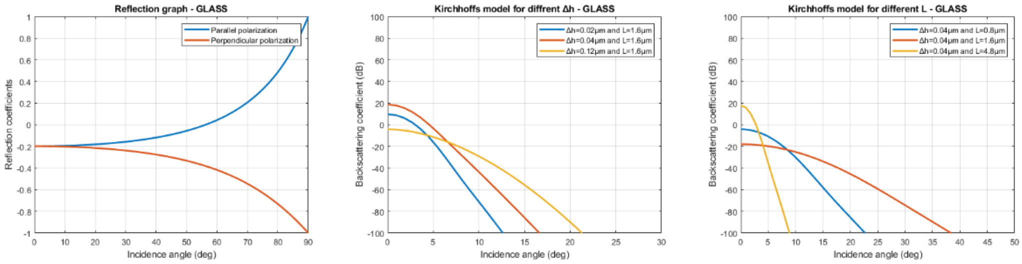

Figure 6. *Angular dependence of: a) Fresnel reflection coefficients for glass material, b) Backscattering coefficient at L constant, c) Backscattering coefficient at* Δ*h constant*

Based on graphs 6b), it can be seen that at a constant value of *L*, at higher Δ*h* the surface scattering by type is closer to Lambert scattering, and at lower Δ*h* it is closer to "mirror" scattering.

3.2. PLASTIC

The refractive index for plastics (plexiglass) is 1.4937 for a wavelength 532 nm. The results are presented in Figures 7a), 7b) and 7c).

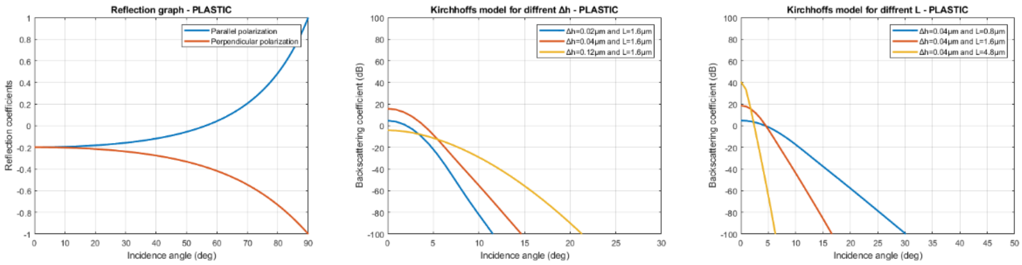

Figure 7. *Angular dependence of: a) Fresnel reflection coefficients for plastic material, b) Backscattering coefficient at L constant, c) Backscattering coefficient at* Δ*h constant*

Since glass and plastic materials have similar reflection characteristics, ie. they have approximately the same values for the refractive index, the graphs of reflection and graphs of the dependence of the backscattering coefficient on the incidence angle are similar.

3.3. COPPER

The refractive index for copper is represented by the complex number 1.1159-2.5956i for a wavelength 532 nm. The calculation of Fresnel coefficients and the backscattering coefficient was done in the same way for the previous materials. The results are shown in Figure 8a), 8b) and 8c).

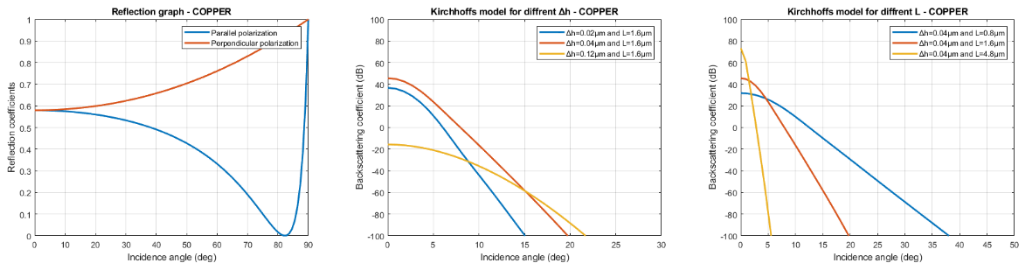

Figure 8. *Angular dependence of: a) Fresnel reflection coefficients for copper material, b) Backscattering coefficient at L constant, c) Backscattering coefficient at* Δ*h constant*

3.4. IRON

The refractive index for iron is represented by the complex number 2.8954-3.9977i for a wavelength 532 nm. The calculation of Fresnel coefficients and the backscattering coefficient was done in the same way as for the previous materials. The results are shown in Figure 9a), 9b) and 9c).

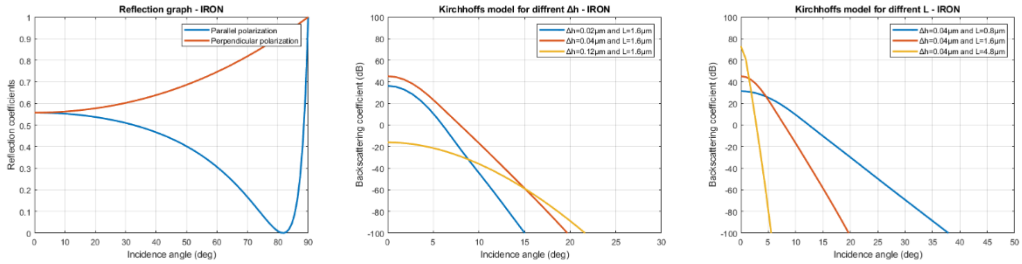

Figure 9. *Angular dependence of: a) Fresnel reflection coefficients for iron, b) Backscattering coefficient at L constant, c) Backscattering coefficient at* Δh *constant*

Copper and iron have similar reflection characteristics, as is the case with glass and plastic, and the graphs of reflection coefficients and graphs presenting backscattering coefficient are almost the same.

- For all tested materials and given values of roughness parameters, it was noticed that when L is constant and approximately $L \geq 3\lambda$, the scattering surface behaves as a mirror at small $\Delta h \approx \lambda/2$ and as Lambert surface at $\Delta h \geq 2\lambda$. In the second case, at constant $\Delta h \approx \lambda$, the scattering surface behaves as a mirror at $L \geq 10\lambda$ and as Lambert surface for $L \leq 1.5\lambda$.
- The maximum angle at which backscattering radiation can be detected for dielectrics from 5-30°, and for metals from 5-40°.
- Fresnel coefficients for metals have higher values than for dielectrics.
- The value of the backscattering coefficient is significantly higher for metallic materials compared to dielectric ones.
- It can be seen from the graphs that although these surfaces can be considered approximately smooth for the given parameters, the type of scattering and the range of angles at which backscattering occurs vary significantly when the roughness parameters are changing.

4. CONCLUSIONS

The main contribution in this paper was the research of the possibility of applying Kirchhoff 's scalar approximation model for determination of backscattering radiation from different types of real materials.

The expression for determining the backscattering radiation coefficient in the Kirchhoff 's model of scalar approximation contains an infinite sum of terms that affect the final value and it has been shown that it is sufficient to use the first 5 terms of that sum.

Surface roughness affects the quality of scanning and the same material has a different coefficient of backscattering radiation and the range of backscattering radiation angles depending on the degree of surface roughness It has been shown that even for materials that are slightly rough and seemingly smooth, the range of angles at which they can be scanned strongly depends on the roughness parameters and they can behave more as a mirror or more as a Lambertian surface.

Using this model, backscattering radiation from dielectric and metal surfaces of different roughness parameters was compared. Based on the presented results, it can be noticed that backscattering coefficients in metals have higher values compared to dielectrics. When comparing materials with the same correlation length L but with different values of Δh, the intensity and angular distribution of backscattering radiation from metallic surfaces vary more significantly with the change of Δh. In a case of the materials with the same rms height Δh the glass surface show the smallest variation in a backscattering coefficients with correlation length comparing with other investigated materials.

Kirchhoff's model of scalar approximation can be used together with the measurement of backscattering radiations at different incidence angles. Based on the obtained modeling curves and measurement results the surface roughness parameters for a certain material can be estimated. This means that the roughness parameters can be estimated from measuring the intensity of the backscattered radiation from the surface at different angles, and using a theoretical scattering model for that type of surface.

The presented parameters of surface roughness can be used when creating a scanning plan. Based on the presented graph types, the range of incident radiation angles for which the backscattering coefficient is optimal can be predicted.

This work was financially supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Grant No. 451-03-68/2020-14/200026).

LITERATURE

[1] J. B. Campbell, and R. H. Wynne, *Introduction to Remote Sensing*, New York, USA: The Guilford Press, 2011.

[2] T. Woldai, "Electromagnetic energy and remote sensing, " in *Principles of Remote Sensing*, 3nd ed., vol. 3. N. Kerle, L. L. F. Janssen, G. C. Huurneman, Ed. Enschede: The International Institute for Geo-Information Science and Earth Observation (ITC), 2004, pp. 29-43.

[3] W. G. Rees, *Physical Principles of Remote Sensing*, Cambridge: Cambridge University Press, 2012.

[4] S. Schröder, A. Duparré, L. Coriand, A. Tünnermann, D.H. Penalver, and J.E. Harvey, "Modeling of light scattering in different regimes of surface roughness," *Optics express*, vol. 19(10), pp. 9820-9835, May 2011.

[5] J. Caron, L. Jacques, and C. Andraud, "Scalar Kirchhoff's model for light scattering from dielectric random rough surfaces," *Optics Communications*, vol. 207, pp. 17-28, June 2002.

[6] Y. S. Kim, "4 to 18 GHz Rader Backscatter Model of Frist-Year Sea Ice," *Korean Journal of Remote Sensing*, vol. 3.2, pp. 89-102, 1987.

[7] L. Sadowski, and T. G. Mathia, "The metrology of ground concrete surfaces morphology with 3d laser scanner," *Management and Production Engineering Review*, vol. 6(2), pp. 40-44, June 2015.

[8] J.M. Bennett, and L. Mattsson, *Introduction to Surface Roughness and Scattering*, Washington, USA: Optical Society of America, 1999.

[9] H. Ragheb, and E. R. Hancock, "The modified Beckmann Kirchhoff scattering theory for rough surface analysis," *Pattern Recognition*, vol. 40(7), pp. 2004-2020, July 2007.

[10] P. Beckmann, and A. Spizzichino, *The Scattering of Electromagnetic Waves from Rough Surfaces*, New York, USA: Pergamon, 1963.

[11] F. Ticconi, L. Pulvirenti and N. Pierdicca, "Models for scattering from rough surfaces," in *Electromagnetic Waves*, vol. 10. V. Zhurbenko, Ed. Rijeka, Croatia: InTech, 2011, pp. 203–226.

[12] K. Tan, X. Cheng, and X. Cheng, "Modeling hemispherical reflectance for natural surfaces based on terrestrial laser scanning backscattered intensity data," *Optics Express*, vol. 24(20), pp. 22971-22988, 2016.

[13] K. Tan, W. Zhang, F. Shen, and X. Cheng, "Investigation of TLS Intensity Data and Distance Measurement Errors from Target Specular Reflections," *Remote Sensing*, vol. 10(7), pp. 1077-1091, 2018.

[14] N. C. Bruce, and J. C. Dainty, "Multiple Scattering from Random Rough Surfaces Using the Kirchhoff Approximation," *Journal of Modern Optics*, vol. 38(3), pp. 579-590, 1991.