A Differential Scattering Probe For Monitoring Road Surfaces

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ABSTRACT

This paper describes an approach we suggest to monitor pavements by using an active optical device. Basically, the amount of light received by such sensors depends on superficial conditions, for which studying some specific traits of scattering indicatrices can bring substantial information. With this objective in sight, the major physical processes originating in the observed back-scattering and opposition effect are simulated. It is shown that several estimators, possibly derived from scattering measurement, are strongly correlated to the macro-texture of the surface. A comparison between computed and measured reflectances is followed by a description of the way planed to turn to account this statement to design a roughness-meter.

I- Introduction

Light scattered by the surface of an object in the visible spectral region is highly sensitive to its small-scale topography. Observations in the near-specular region are often considered to control surface conditions and smoothness (Lukianowicz[1]). Indeed, the whole angular pattern is a potential source of information about texture (Stover[2]), and retro-reflection (referred to as opposition phenomenon or enhanced back-scatter) may be used for monitoring roughness. Such process relies on the solution of an identification problem to extract surface statistics from reflectance measurements, provided the interpretation of data is achieved through the implementation of a non-empirical scattering model.

When roughness is small compared to wavelength, several theories (Kirchhof-related, for instance) are available. For surfaces as rough as pavements, there are few alternatives, since both physical characteristics of the medium and geometry are involved. In this context, we advocate an unusual approach: to develop a light scattering model implementing the classical radiation transport equation (Chandrasekar[3]). Predominant back-scattering behavior of particles is specified through appropriate scattering phase functions (McGuire et al[4]), and a parameterization is introduced to account for the shadow-hiding effects (Iaquinta and Fouilloux[5]). A numerical study is conducted with respect to roughness, to assess the sensitivity of reflectance at a fixed angle of light incidence and for several viewing directions.

II- Method

Starting from a standard radiation transport problem

Likewise during actual roads construction employing superposed material stratums, it makes sense to model the pavement as a horizontally homogeneous plane-parallel structure stratified vertically. Each layer is filled densely and randomly with particles of irregular shape: soil grains. Hypotheses of a turbid medium are fulfilled and we assume no polarization or frequency shifting. In a one-dimensional coordinates system, the monochromatic intensity distribution function I, at depth z in the direction Ω (θ, ϕ), satisfies the conventional radiative transfer equation (Knyazikhin and Marshak[6]):

$$-\cos(\theta)\frac{\partial\, I(z,\Omega)}{\partial\, z}+\sigma_e(z,\Omega_0,\Omega)\, I(z,\Omega)=\frac{1}{\pi}\int_{4\pi}\sigma_s(\Omega'\rightarrow\Omega)\, I(z,\Omega')\, d\Omega'$$

σ_e (z, Ω_0, Ω) is the total interaction cross-section, and σ_s (z, $\Omega'\rightarrow\Omega$) is the differential scattering cross-section for scattering of incoming light from Ω' into a unit solid angle dΩ about Ω. Note that ϕ is the azimuth, and θ the polar angle (with respect to the upward vertical, opposite to the positive z-axis). Boundary conditions are straightforward: the scene is illuminated from above by mono-directional radiation in direction Ω_0, and there is no light source inside the pavement.

Providing a formulation of the extinction coefficient

Basically, grains located near the surface cast shadows on the deeper grains; These shadows are visible for large phase angles, but close to the zero phase angle they are hidden by lighted grains themselves. The consequence is a non-linear increase of the brightness for pavements (as for other rough surfaces), when the scattering angles approach the exact back-scattering direction (Hapke et al.[7]). From a practical point of view,

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the transmission of scattered radiation depends on that of incident radiation, because their optical paths share a common part, free of scatterers, where the transport is not affected. This is a signature in the radiance field which is typical of porous media, because of the finite size gaps (holes or voids) between the grains.

Actually, if they managed to reach a given depth without interception, photons should be able to leave toward an observer without meeting any obstacle at least in the volume common to the incident direction and viewing direction tubes. Based on this principle, and after geometrical considerations related to the shadow-hiding processes, an extinction cross-section was formulated (Iaquinta and Fouilloux[8]). The parameter η that controls the opposition phenomenon (indifferently referred hereafter as hot-spot effect) is proportional to the average size of the holes between soil particles.

Giving an expression of the scattering coefficient

Considering differential cross-section, Henyey-Greenstein[9] function properly describes most particles scattering as a function of the phase angle Θ (between incoming and scattered radiation). The parameters are three: ω_s is the single scattering albedo, b_s describes the angular width of both backward and forward lobes, and c_s regulates their relative amplitude. From a numerical point of view, the parameter b_s takes values in the range of [0, 1[, and the only constraint on c_s is that σ_s remains positive at all angles. However, the scattering phase function of individual soil grains is rather regular, consequently their pattern is usually depicted with a small number of discrete angles (this is sought for using numerical quadratures).

Solving the integro-differential equation

Since the corresponding set of equations is linear in radiance, it is convenient to evaluate the first- and multiply-scattered intensities separately. The analytical solution for the former includes the opposition effect. The contribution of multiple scattering is obtained numerically by applying a variant of the discrete ordinates method named finite-difference exact-kernel (Shultis and Myneni[10]). Following a successive order scattering approach, the source term for the n^{th} scattering event is computed from all the previous scattering orders until convergence of the process (requiring generally a few iterations).

III- RESULTS

Sensitivity of the model to the roughness parameter

As the opposition phenomena mostly affect the single scattering component of reflectances, this study is carried out in the visible domain for which it predominates. Accordingly, bi-directional reflectance factors are represented on Figure-1 as a function of the viewing angle for several values of the parameter η. The plot is in the principal plane (containing the local vertical and the radiation source), because it is where the largest angular variability is expected.

For non-zero values of η, the graphs exhibit the distinctive feature of rough surfaces (located at Ω=-Ω_0 in the retro-incident direction), and when η is large (with η=0.4, and beyond), this phenomenon influences the whole upper hemisphere. On the contrary, for smooth surfaces (η=0) there are no holes between grains then no shadows occur: there is no hot-spot at all (solid line). Between these two extreme situations, as soon as the hot-spot parameter η increases, upward radiance becomes more and more disturbed by the shadow-hiding effect.

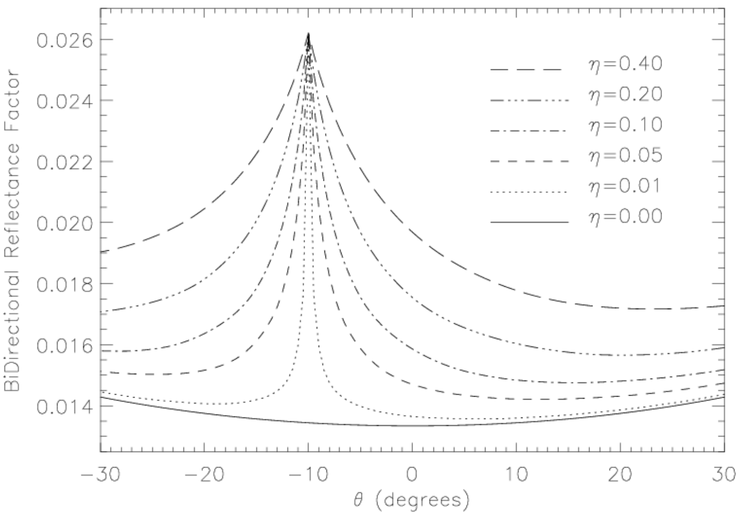

Figure-1: Radiation field emerging from the surface, about the hot-spot peak, as a function of the scattering angle for several values of the opposition parameter η (which is proportional to the roughness).

This situation would be observed, for instance, with the same aggregates (dimensions, material, compaction, *etc.*) but a different surface layout.

Individual particles scattering is considered as isotropic (b_s=0 and c_s=0), and light is incident from direction Ω_0 (10°, 180°).

For a given material (with specific particles scattering properties), all the curves for non-zero values of η pass through the same point located in the retro-incident direction. To some extent, the rougher the surface (and the quantity η) the wider the hot-spot. An experimentally based application of this principle led to the development of high-precision roughness-meters in industry to control finishing operation, inspect polishing, *etc*. Clearly, it is possible to correlate several relevant features of the hot-spot peak, derived from reflectance measurements, to the macro-texture of the surface. When these relationships are not established, interpreting reflectance data remains a problem exemplifying the need for theoretical models for rough surfaces, and in particular pavements.

Comparison against experimental data

A gonio-reflectometer in use at the French Public Works Research Laboratory provides the directional reflectance of road samples as a function of incidence and viewing directions. The light beam is projected *via* three mirrors attached to a lighting arm, and scattered radiation is measured with a photocell at the end of an observation arm which is allowed to rotate independently so as to cover the whole reflectance field. Note that acquiring experimental values is problematical at small phase angles (because of the non null size of the photo-cell, overshadowing the light source) and large zenith angles (at grazing viewing directions).

For a normal light incidence on a sample of asphaltic concrete pavement, measurement and simulation successfully match (Figure-2). Moreover, the model does not encounter any difficulty at small or large phase angles, and the opposition effect peak is perfectly represented.

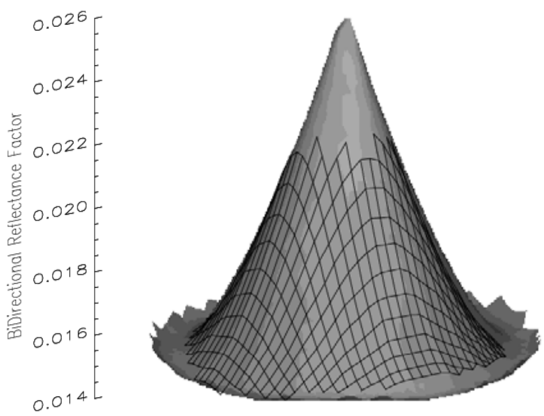

Figure-2: Polar plot of reflectances measured in the laboratory with the gonio-reflectometer (black lines), superimposed on the modeled values (shaded surface).

The zenith angle ranges from 0° (in the center of the graph) to approximately 60° (base of the hot-spot peak), while the azimuth changes counter-clockwise with values of 0° at the back, 90° on the left, 180° in front and 270° on the right.

Roughness assessment strategy

It is now effortless to imagine various quantities to be related to surface properties, in order to develop a device according to the optical characteristics of the material and roughness range of interest. For example, Figure-3a shows how the albedo (as acquired with an integrating hemisphere) vary when the texture changes for $\eta>0.1$: the correlation is unambiguous, and a polynomial fit is sufficient to get η=f (albedo).

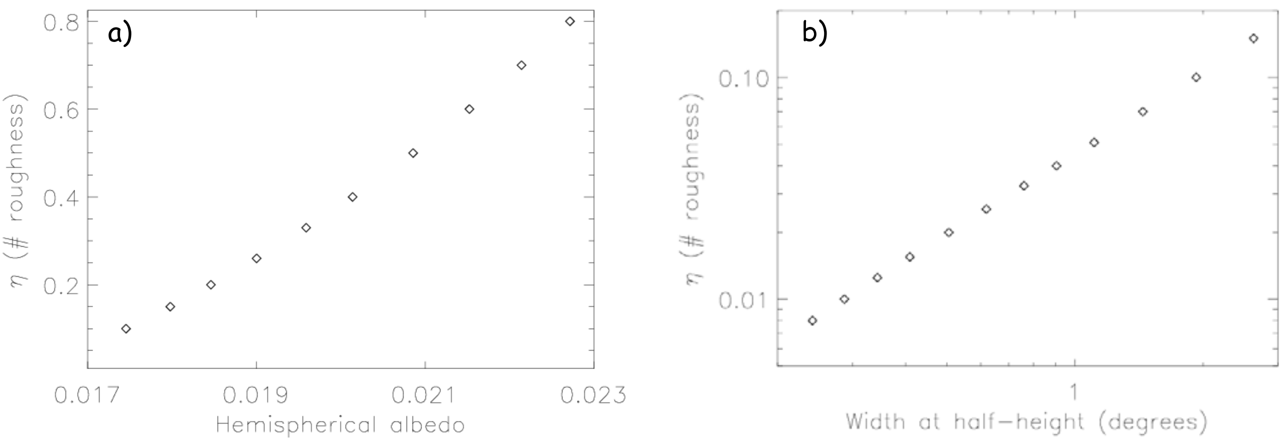

Figure-3: Variation of the parameter η (proportional to surface roughness) as a function of descriptors possibly obtained from reflectance measurements: a) hemispherical albedo, and b) width of the hot-spot at half-height (in a log-log scale).

However, this criterion may not be discriminant enough when the hot-spot is narrow, since the energy content is weak and an accurate measurement of hemipherical reflectance remains a difficult issue. Another quantity, defined as the width of the hot-spot at half-height, is also pertinent, specially for $\eta<0.2$ (Figure-3b). There is a linear relationship between the angular aperture of the hot-spot peak and the roughness parameter. Therefore, provided data are available in the first degrees on one side or other of the retro-incident direction (or even both), such information proves to be very meaningful.

Design of a differential scattering roughness-meter

An instrument conceived on this line for a continuous record of pavements' macro-texture (onboard an anonymous vehicle inserted into the traffic flow), will take advantage of the differential scattering approach. Schematically (Figure-4), the target surface is illuminated vertically, and light distribution after interaction is measured in a small solid angle using photo-detectors (array of photodiodes arranged on an arc, CCD matrix, optical fibres, *etc*). This sensor is connected, *via* a data acquisition board, to a micro-computer in charge of the processing. Seeing what we established here above, the pavement roughness characteristics deduced with this method should be compared to those obtained with a so-called sand patch texture measurement (which is far more tedious).

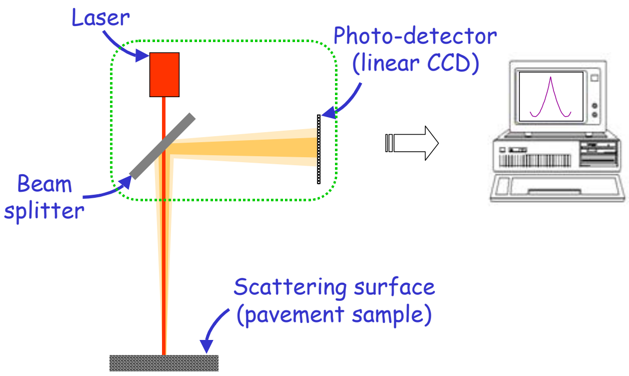

Figure-4: Simplified schematic diagram of what could be a scatterometric roughness meter having a vertical light incidence and making measurement in the back-scattering (precisely in the hot-spot region).

IV- CONCLUSION

We developed a new bi-directional reflectance model for rough scattering surfaces, making use of four parameters having a physical meaning: three of them characterize the optical properties of the media, and the fourth one controls the structural characteristics (texture). Realistic radiation fields emerging from pavements are simulated without difficulty in any illumination and observation condition, with no loss of information at small and large phase angles. A comparison with actual measurements confirmed the capability of the model for situations where no other data were available.

This model was used for a sensitivity study indicating that the roughness of a sample and its scattering behavior are closely connected. An illustration was presented with, as example of indicators, the width of the hot-spot peak and the hemispherical albedo. These are preliminary results, but it seems possible to monitor the macro-texture of the pavements from suited angular observations of scattered light. There is still work to be done, in particular to investigate the technique's robustness, but this is a promising and powerful method for remote inspection of road surfaces.

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