Activities in imaging through fog at CD6: polarized light propagation modelling

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***Abstract*— Currently, in CD6, a new line of research devoted to polarimetric imaging is being developed. The use of polarization adds new information that is not reachable using other conventional imaging modes. In addition, recent literature explores the capability of using polarized illumination and detection to extend the range and enhance image contrast in turbid media such as fog, dust or smoke. Different computational and experimental tools are presented, in order to study polarized light behavior when propagating through foggy media.**

Keywords—scattering, light propagation, polarization, Monte-Carlo, turbid media, fog, fog-chamber

I. Introduction

The Centre for Sensors, Instruments and Systems Development CD6 is a technological innovation centre from Universitat Politècnica de Catalunya (UPC) which operates in the field of Optical Engineering. The activity of CD6 aims to create value through innovation. Applied research developed by CD6 is defined in order that the new knowledge generated reaches the market as new products or new processes in different fields.

In security applications, optical and photonic technologies can play a key role. Areas such as safety in driving all types of vehicles, sensors and pollution in air quality control are issues of crucial importance and optical devices can give out effectively. At this moment, we are working on improving sensing through foggy media, characterized by water droplets suspended in air. In order to face this problem, a new line of research devoted to polarimetric applications is being explored in CD6. Polarimetric imaging have showed outperformance specifications towards increasing visual contrast in these kinds of turbid media [1]—[3]. This polarimetric line of research is complementary to other active lines in our centre such as conventional imaging, spectral imaging and lidar imaging in our centre. Our goal is to evolve towards multimodal solutions, in which polarization is expected to provide a complementary approach to the other settled imaging technologies.

Currently, we are developing different tools (models and experimental setups) for studying polarized-light behaviour in foggy environments, in order to design the most suitable sensing configuration.

II. Methods

A. Modelling

For the description of the physical phenomenon of energy transfer in the form of light through a turbid media, the balance of incoming, outgoing and absorbed and emitted photons is used. The basic theory that allows to calculate light distributions in multiple scattering media with absorption is the radiation transfer theory (RTT). Its core is the radiation transfer equation (RTE), a balance equation characterizing the flow of photons in a given volume element that considers their velocity, position and changes due to scattering and absorption. RTT can include a vectorial approach to consider polarization, becoming a fully coupled vector radiative transfer (VRT) model which enables the photopolarimetric radiative transfer formulation. Solving it for some scattering regimes, complex geometries, non-uniform distribution of scatterers, etc. may be difficult, highly time-consuming or even impossible. In these cases, RTE requires simplifications and/or the use of computational approaches [4].

Currently, the standard computational method used for giving approximated solutions to these unsolvable cases is Monte-Carlo (MC) approach based on Stokes-Mueller formulation for vectorial from. Due to the versatility of the method, it is more suitable for a general inspection of different aspects of light propagation and light/object interaction or for modelling imaging, than other techniques or commercial software available.

Now, it is desirable to present polarization in the mentioned Stokes-Mueller formulation. The state of polarization and intensity of a beam is specified by a 4x1 vector, known as Stokes vector **S**. S_0 corresponds to the total intensity of the light, S_1 is the difference between linear horizontally polarized and linear vertically polarized flux, S_2 gives the difference between the linear 45° and linear 135° polarized flux, and S_3 is the difference between right and left circularly polarized flux. The Stokes parameters are time averages; therefore, no coherence effects are considered [5].

When Stokes vectors are used to describe the propagation of light through optical components, each of these components can be represented uniquely by a 4x4 Mueller matrix **M** (MM). Consequently, when the Stokes-Mueller formalism is employed to describe scattering events, the scattering properties of a medium are defined by the Mueller scattering matrix (MSM). By multiplying the Stokes vector of the incident polarization state with this MM, one obtains the resulting Stokes vector of the scattered light [6].

Extinction properties and MMs of a turbid media can be computed using Mie Theory [7]. It gives quantitative results of the interaction of an electromagnetic plane wave by a single homogeneous sphere, being likely the most important exactly soluble problem in the theory of absorption and scattering by small particles. As a complete electromagnetic solution, it can also be presented considering polarization. The scattering properties of the medium are defined by a MM called the

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MSM. This MM transforms the Stokes vector of the incident light beam into the Stokes vector of the scattered light beam. For scattering by a medium composed of spherical scatterers, this matrix can be rigorously derived by the use of the Mie theory for each scattering angle ϑ.

A foggy environment is an example of turbid media (as are biological tissue, nebulous media, colloids, murky waters or clouds) which can be optically characterized by an absorption coefficient μ_a, scattering coefficient μ_s, an anisotropy factor g and different MSMs. Fog standard definition is "a visible aerosol consisting of tiny activated water droplets suspended in the air, in vicinity of the earth's surface that reduces the horizontal visibility below 1 km"; thus, modelling it as a composition of very fine droplets of water (assumed to be spherical) suspended in air is a good approximation; and it shows good results when inspecting the bibliography. The water droplets act as light scatterers, being the responsible of the reduction of the visibility near the ground surface. By knowing the distribution of droplets and considering them homogeneous, Mie Theory can be applied to calculate the optical parameters and characterize the medium. Thus, it is possible to computationally study propagation of polarized light through it [8].

B. *Experimental setup for fog simulation*

In order to study light propagation in turbid media, along with modelling, several experimental setups have been proposed. Beside experiments in real outdoor scenes, laboratory experimental testing is characterized for being performed in a known media in which some of the properties are controlled. In the past, beyond the global optical properties, the characteristics and the way that the turbid environment was produced were not relevant, so this information was not deeply detailed in methodology sections, sometimes showing only slight references to the chemical composition.

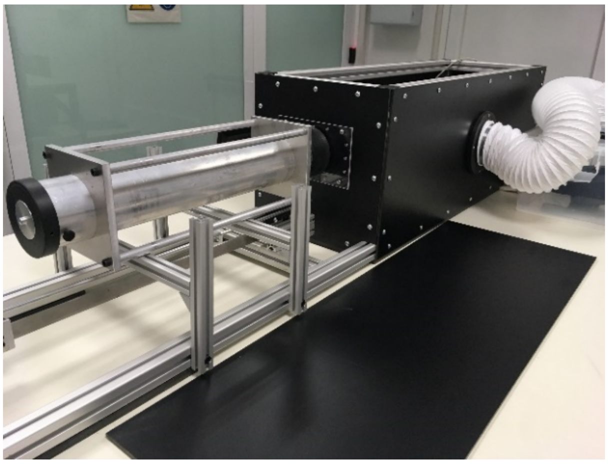

Fig. 1. Experimental setup for simulating fog conditions

However, nowadays, with the novel applications of vision through fog (transport, security, military…), the need to have controlled spaces for reproducing real foggy environments, or any comparable atmospheric disturbance or turbid media, grows in relevance. This kind of experimental setup framework are the so-called fog chambers. They are used for validating developed models against simulated real conditions, investigating and testing the performance of sensors in different conditions or just working with light properties.

It is remarkable the existence of the state-of-the-art large-scale fog chamber infrastructures, that reassemble on-road conditions for car testing [9]. However, those are not the only ones available. Simpler self-built chambers are also being designed and used at different labs. They are established as an easier and more modest working method enabling to validate models. Usually, they are built using a smoke generator or humidifier and some space to confine that media (tent, box…). The way in which fog density is controlled is variable and the control of many parameters is difficult to attain. However, it is possible to obtain relevant data, and in some cases show the actual performance in fog giving good results. Constructing a "box" with these characteristics enables the researcher to test in smaller scale their hypothesis or optical designs before accessing a larger infrastructure. At CD6, a small-scale fog-chamber has been built, using an ultrasonic-humidifier and fans; encapsulated in a box made by water-proof materials. Our fog-chamber is shown in Fig. 1 and 2.

III. RESULTS

We are interested in evaluating how a turbid media (as generalization of foggy conditions) affects the polarized light (and light in general) for imaging applications. In particular, for the case of using an active-system for intentionally illuminating the scene. For that propose, a Monte-Carlo model for solving RTT in these conditions is implemented.

A. *Backscattering temporal shape*

When light first interact with fog, generated backscattered directly blinds the sensor of the imaging device. This is the first faced problem: the saturation of the detector just after light is sent. That is why, the temporal response of a backscattered light pulse has been study, in order to characterize its shape and influence.

Temporal behaviour of received light signals in different situations is compared. In all cases, a light pulse of total energy 1 mJ, FWHM width of 1 ns and cantered in initial time 0 is used. Firstly, it is validated the expected behaviour of the pulse when propagating through a slightly scattering air media (μ_s=0.01 cm^{-1} and g=0.9). The pulse is steered towards a 100% reflective target placed at 0.5 m. The returned pulse is cantered at 3.33 ns; which corresponds to twice the distance to the object.

Fig. 2. Foggy evolution inside a small-scale fog-chamber

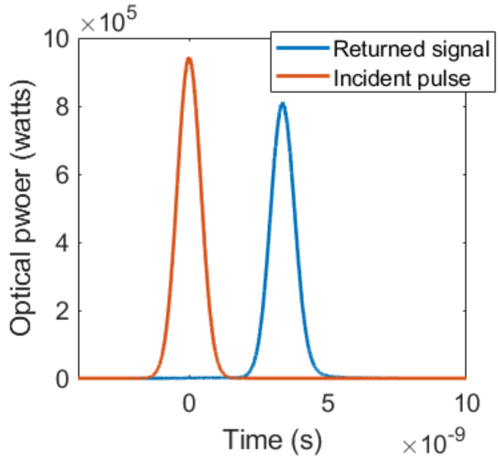

Fig. 3. Simulation of initial and received signal through a slightly scattering media in the presence of a reflective object placed at 0.5 m

The total received energy is smaller due to scattering extinction effect. The results are shown in Fig.3.

Then, the pulse is sent through different media with high scattering coefficients: μ_s=10 m^{-1}, 20 m^{-1}, 30 m^{-1} and 50 m^{-1}. These conditions would reassemble a dense foggy environment. In this case, all the received energy is as a result of the backscattered light of the media. As it may be expected, the bigger the coefficient, the greater the amount of energy backscattered. As shown in Fig. 4, detected backscattered signals have the same particular shape.

Finally, the procedure is repeated in the same four different media conditions in the presence of the 100% reflective object at 0.5 m. The results obtained are shown in Fig. 5. It is observed that around the expected position of the object (3.33 ns), the peak corresponding to its presence appears along with the backscattering contribution. In addition, it is possible to evaluate what is the level of scattering at which the target is no longer detected (it is not distinguishable from the backscattering signal), so it would not be possible to obtain its image.

Due to greater light extinction in a more scattering media, the reflected signals are less and less energetic. The optical power pic is four to five times smaller than in air. However, it is seen that, whenever it is detectable, it keeps its initial Gaussian shape. On its side, backscattered light also keeps its shape. So, we can conclude that regardless the loss of energy, both signals are independent. Thus, they could be fitted as the sum of both expected shapes: Gamma distributions for backscattered light and Gaussian distributions for reflected signal [10]. Those fitting distributions are applied in our results (see Fig. 6), obtaining values of coefficient of determination are almost 1.

Controlling the time and shape at which backscattering will return to the detector, could be used to discard it and, hence, obtaining better images in foggy conditions**.**

B. Polarimetric characterization of turbid media

The other issue in which we are deeply interested is the polarimetric behaviour in different turbid conditions. We expect to take advantage of polarization memory effect for improving contrast visualization. MC techniques to simulate the propagation of light of polarized light in turbid media are based on the Stokes-Mueller formulation. Except for some differences, the general scheme of the polarized approach is

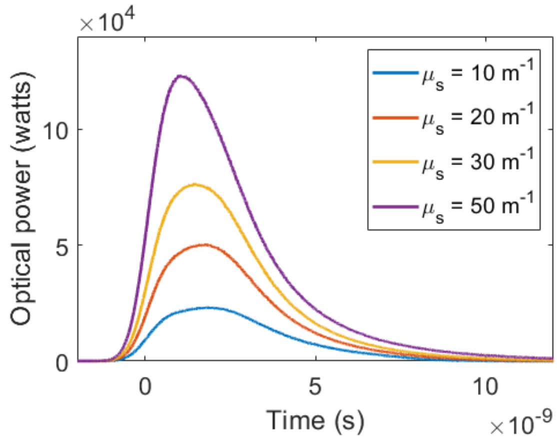

Fig. 4. Simulation of detected backscattering light signal in turbid media with g=0.9 for different scattering conditions

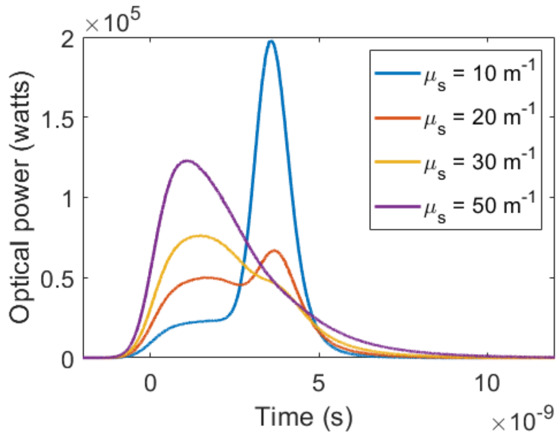

Fig. 5. Simulation of detected backscattering light signal in turbid media with g=0.9 in the presence of an object for different scattering conditions

similar to those of the scalar approach. At each photon step, its Stokes vector is scattered and it changes according the MSM deduced from Mie Theory at that specific scattering angle for that media and wavelength [11].

In order to inspect the polarimetric backscattering characteristics of a medium, a polarimetric MC is used for computing its backscattering Muller matrix [12]. The results are represented as a combination of 4x4 figures, which relate the incident and received components of the Stokes vector. Thus, it is possible to foresee how each of the polarization components would be affected. In fact, obtained figures are used to define the backscattering matrix of a media for each of the image pixel. Moreover, when studying an unknown media, they may be used to deduce its optical properties.

An example of its implementation and the results obtained is shown in Fig.7.

Studying and obtaining the backscattering MM for a foggy environment, would be used to completely characterize the backscattering characteristics of the media. Moreover, it may be used to select the combination of polarization components more useful for different situation.

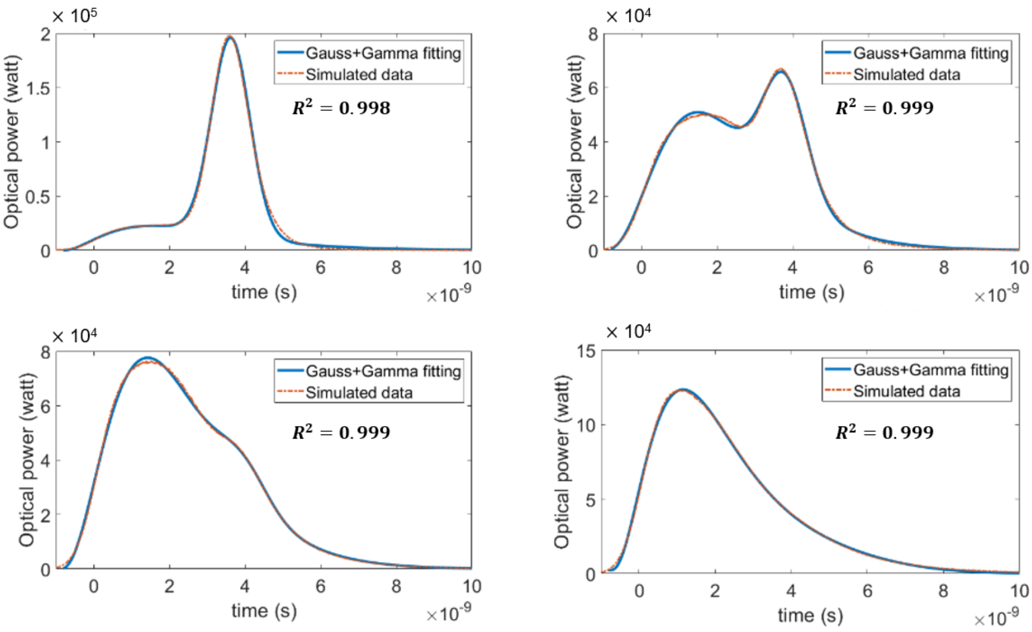

Fig. 6. Fitting of simulated signals from Fig.5. From left to right, up to down: μ_s=10 m^{-1}, 20 m^{-1}, 30 m^{-1} and 50 m^{-1}.

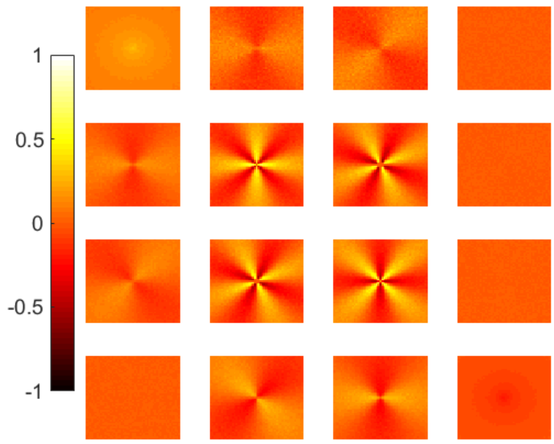

Fig. 7. Simulation of a normalized backscattering MM for an aqueous suspension of spheres of radius 100 nm and refractive index 1.59

IV. Conclusions and Future work

The obtained MC model and the experimental setup is expected to be used to study the propagation of polarized light under different conditions in turbid media. In particular, the following features are considered very relevant:

- Backscattering phenomena of active illuminators due to the first interaction with the environment
- Depolarization effects in propagation and its wavelength dependence
- Optimal polarization configuration sensing to improve contrast-to-noise ratio for imaging (CNR) and for radiometric detection
- Reflectivity of materials and behaviour of polarization states under foggy conditions; and
- Evaluation of the performance of polarimetric Full-Stokes camera.

Acknowledgment

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