Journal of Quantitative Spectroscopy & Radiative Transfer 146 (2014) 431–443

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Active imaging systems to see through adverse conditions: Light-scattering based models and experimental validation

Nicolas Riviere *, Romain Ceolato, Laurent Hespel

Onera, The French Aerospace Lab, 31055 Toulouse, France

ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form
26 March 2014
Accepted 30 April 2014
Available online 24 May 2014

Keywords:
Adverse conditions
Bad weather conditions
Light scattering
Laser imaging
Defense
Security

ABSTRACT

Onera, the French aerospace lab, develops and models active imaging systems to understand the relevant physical phenomena affecting these systems performance. As a consequence, efforts have been done on the propagation of a pulse through the atmosphere and on target geometries and surface properties. These imaging systems must operate at night in all ambient illumination and weather conditions in order to perform strategic surveillance for various worldwide operations. We have implemented codes for 2D and 3D laser imaging systems. As we aim to image a scene in the presence of rain, snow, fog or haze, we introduce such light-scattering effects in our numerical models and compare simulated images with measurements provided by commercial laser scanners.

1. Introduction

Vision systems are often designed to perform in clear weather where the observers and systems are in the air. We assume that this embedding medium is transparent at the wavelengths considered. We also assume the light rays to be propagated from the light-source to the observer without attenuation or alteration after reflection from a target. For outdoor and real-time applications, we need to analyze the impact of atmospheric and bad weather conditions on vision systems which includes the effects of light-scattering because weather conditions may influence the incidence of aircraft accidents in a number of ways. One example is when an Airbus A380, taxiing along the runway of JFK Airport in New York, clipped the wing of a smaller CRJ jet on April 11th 2011 and sent the CRJ into a spin. There were no reports of injuries but both aircraft were grounded pending an investigation. The accident was mainly due to bad weather (strong rain) and low visibility (night vision) conditions.

We identified different sensor technologies in order to detect, recognize, and localize objects of a scene in all weather conditions (rain, snow, fog, haze, dust wind…). Providing enhanced vision to a driver or the crew of an aircraft should help reduce accidents. One can distinguish two kinds of sensors to fulfill this objective: large Field of View (FOV) sensors (passive visible/IR cameras, radar) and, high spatial resolution – small FOV optical laser sensors prototypes. Large FOV sensors technologies are often chosen to offer the best solution to a pilot to maneuver on a taxi way. Small FOV sensors are dedicated to recognize and to localize fixed and mobile objects. We plan to improve obstacle detection, the localization of obstacles previously detected, and the recognition of these objects.

Here, we develop and model active imaging systems to understand the relevant physical phenomena impacting their performance. For small FOV applications, we distinguish between 2D and 3D active imaging devices as the description of the physical phenomena can be different in these two cases [1,2]. Efforts have been made on both the

* Corresponding author.
E-mail address: nicolas.riviere@onera.fr (N. Riviere).

http://dx.doi.org/10.1016/j.jqsrt.2014.04.031

propagation of a pulse through the atmosphere (*e.g.* scintillation and turbulence effects) and, on target geometries and their optical properties (*e.g.* radiometric and speckle effects). For numerous applications, these imaging systems must operate in all-ambient illumination (day and night vision) and weather conditions in order to perform strategic surveillance of the environment for various worldwide operations. We have implemented codes for both 2D and 3D laser imaging systems. As we aim to image a scene in the presence of rain, snow, fog or haze, we introduce such meteorological effects into these models and compare simulated images with measurements provided by commercial imaging systems. As a consequence, this paper will focus on the description of the scattered light by various meteorological events. We then describe numerical models and compare simulated and experimental results.

2. Light-scattering from bad weather conditions

Weather conditions differ mainly in the types and sizes of the particles involved and their concentrations. Efforts have gone into measuring the particle sizes and their concentrations for a variety of conditions. Given the small size of air molecules, relative to the wavelengths of visible light, scattering due to these molecules is minimal. We will refer to the event of pure air scattering as a clear sky (by day or night). Larger particles produce a variety of weather conditions, which we briefly describe below.

2.1. Definitions of meteorological events

Haze has a diverse set of sources including volcanic ash, foliage exudation, combustion products, and sea salt. The small particles suspended in the air, produced by these sources, respond quickly to changes in relative humidity and act as nuclei for small water droplets. Haze particles are larger than air molecules but smaller than fog droplets, which tends to produce a distinctive gray or bluish hue that affects visibility.

Fog appears when the relative humidity of an air parcel reaches saturation. Then, nuclei grow by condensation into water droplets. Fog and certain types of haze have similar origin and an increase in humidity is sufficient to turn haze into fog. This transition is quite gradual and the intermediate state is referred to as mist. While perceptible haze extends to an altitude of several kilometers, fog is typically just a few hundred meters thick. A practical distinction between fog and haze lies in the greatly reduced visibility due to the former. There are many types of fog (*e.g.* radiation or advection fog), which differ from each other in terms of their formation processes.

Rain and snow are other typical meteorological events. Rain causes random spatial and temporal variations in passive images and must be dealt with differently from more static weather conditions. For active images, rain introduces bad pixel returns. Similar arguments apply to snow, where the flakes are rough and have more complex shapes and optical properties.

2.2. Light-scattering from meteorological events

In this section, we present the evolution of the typical optical properties of various hydrometeors such as fog, rain and snow. We identified three wavelengths in the visible–SWIR bands (respectively $\lambda_1=500$ nm, $\lambda_2=900$ nm and $\lambda_3=1550$ nm). We assume the fog and raindrop to be spherical to evaluate their backscattering and their extinction coefficients using the Mie theory.

We compute the scattering Q_{sca}, the extinction Q_{ext} and, the backscattering Q_{back} efficiencies for ice crystals and water spheres at two fixed wavelengths (λ_1 and λ_3). The backscattering efficiencies decrease and tend to the Fresnel coefficients at normal incidence for large particles (diameter > 1 mm) in the SWIR band. This phenomenon occurs when the absorption in the particle suppress internally reflected rays.

Let us introduce $N(d)$ as the Particles Size Distribution (PSD) given by a Gamma modified model. This model was previously described by Deirmendjian [3]. Extinction and backscattering coefficients for fog [4,5], rainfall and snowfall [6–8] can be derived from $N(d)$. The PSD is mainly dependant on the rain (or snow) rate. In snowfall cases, we also consider the density of the particles and distinguish wet from dry snow.

Fig. 1 illustrates the extinction α and backscattering β volume coefficients [26] and their corresponding PSD limited to the three wavelengths selected. The fog shows a high extinction and backscattering coefficient (from 5×10^{-3} to 1.5×10^{-2} m^{-1}). Moreover, α increases in the SWIR band. Even if the extinction is spectrally constant in the visible–SWIR range for rain and snowfall, the backscattering coefficient decreases in the SWIR band. This is due to a lower back-efficiency for particles larger than 1 mm and the scale of rain-droplet (or snow-crystal) size (from 1 to 2 mm).

The number of particles contributing to the backscattering signal is $N=4\cdot\beta\cdot V/Q_{back}\cdot\pi\cdot d^2$. The probe volume V is adjusted to 10^{-3} m^3. On the one hand, a mean particle size of 10 μm is introduced (monodisperse PSD) for the fog case. We evaluate more than 10^4 particles. On the other hand, the mean diameter of raindrops (or snowflakes) is set to 1.5 mm. In those cases, we obtained $N<1$. The classical backscattering approach cannot describe the phenomena occurring during the pulse propagation.

2.3. Influence of light-scattering on imaging systems

Bad weather conditions also have an impact on the target reflectivity and relative contrast with the background [9,10]. For instance, the reflectivity of asphalt, painted or unpainted is modified by the surface uniformity (moist or wet surfaces, covered by dust or snow). Kerekes et al. [11] illustrates the reflectivity evolution for various materials under rainfall. Here, we assume the reflectivity of an object to be the same as the background. Simulations will be done in this paper according to Table 1. Weather conditions also impact the ground solar irradiance and the atmospheric diffuse specific-intensity (E_λ and L_λ, respectively). In this paper, we distinguish two extreme cases where the values are assumed to be