Influences of extinction coefficient profile on the estimation of Slant Visual Range

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HIGHLIGHTS

- We estimate Slant Visual Range in the Taklimakan Basin for sand-dust weather.
- Extinction coefficient profile can be categorized into 3 patterns.
- Aerosol is roughly dust type in lower layers.
- Two methods are introduced to estimate Slant Visual Range.
- Slant Visual Range is estimated at large hit rates for the two methods.

ARTICLE INFO

ABSTRACT

Slant Visual Range (SVR) is defined as the distance at which the contrast of a given object with respect to its background is just equal to the contrast threshold of an observer in slant direction. In this study, estimation methods and errors of SVR are explored in lidar-free circumstances where Extinction Coefficient Profile (ECP), vertical distribution of Single Scattering Albedo (SSA) and asymmetry parameter (ASY) cannot be acquired. Statistical characteristics of aerosol optical properties in the Taklimakan Basin for sand-dust weather are derived from the CALIPSO daytime aerosol product from 2011 to 2014. SSA and ASY are approximated as 0.92 and 0.7 because aerosol types are mainly dust and polluted dust throughout layers. Besides, ECP can be categorized into exponential, Gaussian and other patterns. Based on whether the determination of real ECP into one of the three patterns is feasible, two SVR estimation methods are introduced and termed the accurate estimation method (AEM) and the blind estimation method (BEM), both methods are performed using SBDART radiative transfer model. For the AEM, analysis of estimated SVR and real SVR reveals a minimum linear correlation coefficient of 0.98 and a maximum root mean square error of 0.07, and the hit rate (R) of SVR estimation increases from 86% to nearly 100% when the maximum allowable relative error (MARE) increases from 10% to 25%. Validation of the BEM shows that R varies from 78% to 100% for MARE of 25% and falls drastically with the decrease of MARE, with the highest R value in spring and summer for the Gaussian pattern and the lowest values in fall and winter for exponential and other patterns. This study is among the first to explore the feasibility and methodology of deriving SVR in lidar-free circumstances.

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1. Introduction

Confusion may arise with the term Slant Visual Range (SVR) in

existing research. Streicher et al. (1993) indicated that SVR depends only on the turbidity of the atmosphere and identified SVR with slant visibility (SV), which is completely different from the SV promoted by Wang and Rao (2003), who demonstrated that SV is more than a function of atmospheric turbidity. However, Ruppersberg and Schellhase (1979) adopted Slant Meteorological Visibility (SMV) to depict the turbidity of the atmosphere. For uniformity, the parameter depicting atmosphere turbidity is hereafter called SMV. SMV is measured as the distance at which transmittance attenuates to a pre-defined threshold value such as

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0.05. According to the World Meteorological Organization (2008), visual range is defined as the distance at which the luminance contrast of a given object with respect to its background is just equal to the contrast threshold of an observer. The definition is adapted to any direction. Visual range thus appears in the literature to be more than an atmospheric optical parameter. In this study, Slant Visual Range (SVR) specifies the visual range in slant direction and is different from SMV.

SVR has important uses in many fields including astronomical observation, remote sensing, image matching, object recognition, guidance technology, spacecraft landing and takeoff, and space search and rescue (Werner, 1981; Wang et al., 2004; Smith and Cochrane, 2011). For example, SVR was once a limiting factor in the search for the missing Malaysian Airlines Flight MH370 aircraft. However, techniques for measuring SVR are still under exploration. Existing research focuses on the detection of SMV (Tian et al., 2012). In that SMV research, lidar is the most widely used tool to detect vertical structures of atmospheric optical properties (B. Chen et al., 2013). Wang and Rao (2003) developed the theoretical basis for SVR calculation and showed that SVR depends on the Extinction Coefficient Profile (ECP) and the radiance profile. ECP can be retrieved by lidar signals, while measurement of radiance profile is difficult (Rao, 2010). However, radiance profile can be simulated by a radiative transfer model given the variables geometrical condition, ECP, single scattering albedo (SSA) and phase function. In circumstances lacking lidar, ECP and profiles of other optical properties are usually not acquired, which poses challenges for the estimation of SVR.

To explore estimation methods and errors of SVR in lidar-free circumstances, the influence of ECP on SVR is investigated for sand-dust weather in the Taklimakan Basin ($36°-42°$N, $75°-90°$E). This basin is chosen because sand-dust weather drops atmospheric visibility drastically and occurs most frequently in this region (Huang et al., 2008). Statistical characteristics of ECP in the Taklimakan Basin are derived from the CALIPSO aerosol product from 2011 to 2014, and the estimation error of SVR is discussed. The remainder of the paper is organized as follows. Section 2 briefly presents the methodology of SVR calculation, section 3 gives a brief introduction to the data and model used in the study, section 4 explores characteristics of ECP to lay the foundation for SVR estimation, section 5 gives results and analyses, and section 6 summarizes general discussions and conclusions.

2. Methodology of SVR calculation

The geometrical condition for SVR observation is shown in Fig. 1, where the subscript s and v are the abbreviation of solar and viewer, and z and z_0 denote sea-level elevation of the viewer and the un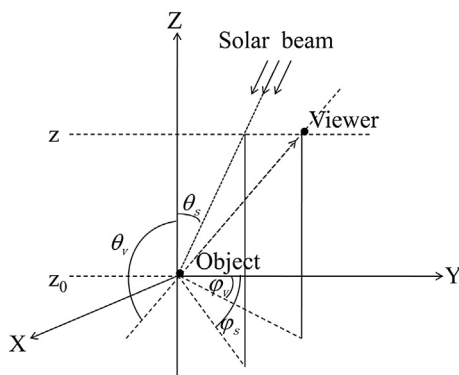derlying surface. In this study, the object is observed in air-to-ground direction from the viewer's line of sight, and SVR represents air-to-ground SVR hereafter unless otherwise noted. Zenith and azimuth angle are denotes by θ and φ. θ is measured from the Z axis to the incoming direction, and φ is measured clockwise from the Y axis to the horizontal projection of the radiative transferring direction.

Whether the target can be recognized at altitude z depends on the target-background luminance contrast C_{ob}. SVR is taken as the distance L where C_{ob} reaches the threshold value of target-background luminance contrast C^t which is set to 0.05, the value adopted in runway visual range measurements in airports. Due to the finite nature of the object's size, perturbation of background radiance by the object is negligible. The background with an object laid on it can be treated as a uniform Lambertian reflector. Accordingly, C_{ob} can be expressed as (Wang and Rao, 2003)

$$C_{ob}(\mu, z) = \frac{|I_0(\mu, z_0) - I_b(\mu, z_0)|}{\max[I_0(\mu, z), I_b(\mu, z)]} \cdot \exp\left(\frac{\int_{z_0}^z k(z')dz'}{\mu}\right) \quad (1)$$

where I_0 and I_b denote the luminance of target and background, μ is cosine of viewing zenith angle, and $k(z')$ denotes ECP. For the purpose of simplification, $C_{ob}(\mu, z)$ is rewritten in the form

$$C_{ob}(\mu, z) = C_{ob}(z_0) \cdot f(\mu, z) \cdot T(\mu, z) \quad (2)$$

where $C_{ob}(z_0)$, $f(\mu, z)$ and $T(\mu, z)$ can be expressed as Equations (3)–(5):

$$C_{ob}(z_0) = \begin{cases} (\rho_{sur} - \rho_{obj})/\rho_{sur}, & \rho_{sur} > \rho_{obj} \\ (\rho_{obj} - \rho_{sur})/\rho_{obj}, & \rho_{sur} \leq \rho_{obj} \end{cases} \quad (3)$$

$$f(\mu, z) = \begin{cases} I_b(\mu, z_0)/I_b(\mu, z), & I_b(\mu, z_0) > I_0(\mu, z_0) \\ I_0(\mu, z_0)/I_0(\mu, z), & I_b(\mu, z_0) \leq I_0(\mu, z_0) \end{cases} \quad (4)$$

$$T(\mu, z) = \exp\left(\frac{\int_{z_0}^z k(z')dz'}{\mu}\right) \quad (5)$$

ρ_{obj} and ρ_{sur} in equation (3) denote reflectance of the object and background, respectively. As is shown in equation (2), $C_{ob}(\mu, z)$ is composed of 3 parts: the inherent target-background luminance contrast $C_{ob}(z_0)$, transmittance $T(\mu, z)$ and $f(\mu, z)$. $C_{ob}(\mu, z_0)$ is only related to ρ_{sur} and ρ_{obj}, and $T(\mu, z)$ is directly calculated from ECP. $f(\mu, z)$ is determined by layered radiance $I(\mu, z)$, which can be calculated by the SBDART radiative transfer model. ECP, vertical distribution of SSA and phase function are necessary input parameters for modeling.

3. Data and model

3.1. CALIPSO data

The CALIPSO daytime aerosol product from 2011 to 2014 is used to generate statistical characteristics of aerosol optical properties in the selected region. CALIPSO is a member of the A-Train constellation of satellites rounding the earth with a 96-min period; it makes global observations of 3-dimensional structures of optical properties of aerosol and cloud feasible over a 16-day period. As one of the three payloads on CALIPSO, the Cloud-Aerosol Lidar with

Fig. 1. Geometry of air-to-ground SVR observation.