Application of Cloud Occurrence Climatology from CALIOP to Evaluate Performances of Airborne and Satellite Electro-Optical Sensors

A. BIZARD, K. CAILLAULT, C. LAVIGNE, A. ROBLIN, AND P. CHERVET

Theoretical and Applied Optics Department, Office National d’Études et Recherches Aéronautiques, Palaiseau, France

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ABSTRACT

A wide variety of optronic sensors, on board a satellite or airborne platform, are used for remote sensing, surveillance applications, and telecommunications. Cloud presence in the field of view is one of the key factors limiting the performances of these sensors. Consequently, cloud presence must be taken into account in order to evaluate their performances. To that end, a Monte Carlo method is used. Geometrical and optical cloud properties necessary to build the model are obtained from Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) measurements that enable one to deal with the optically thinnest clouds. Different viewing geometries are presented, corresponding to surveillance missions by an airborne sensor with close-to-the-horizon viewing and to an optical link between an aircraft and a satellite. Results obtained are compared to a previous study and improvements reached with this new method are discussed.

1. Introduction

The electro-optical performance of an airborne or a satellite sensor used for remote sensing, surveillance, or telecommunications can be strongly affected by cloud presence along its line of sight (LOS). Clouds can either produce an attenuation of the target signal or an increase in background radiation because of thermal emission or sunlight scattering. The impact of high-altitude clouds along the LOS has been studied for various applications, such as hot sources detection in the infrared domain (Liou et al. 1990) and laser transmission (Liou et al. 2000; Ou et al. 2002). However, these studies do not consider the statistical aspects of cloud occurrence. Getting transmittance statistics is also an important challenge to a number of applications, such as ballistic missile defense, ground data collection, laser communications, and detection of targets through the atmosphere. Estimation of the probability of a cloud-free line of sight (CFLOS), that is, the ability to obtain a LOS through the atmosphere unimpeded by cloud presence, has been widely documented (Shields et al. 2005; Lund and Shanklin 1972, 1973; Lund et al. 1980; Hobbs et al. 2003; Chervet and Roblin 2006) for applications such as laser communications and missile defense. Cloud statistics taken into account in these studies rely on data from passive meteorological sensors that provide a reasonable measurement of cloud top altitudes, but do not provide information about cloud bases or multilayered clouds (Stubenrauch et al. 2006; Wylie and Menzel 1999; Wylie et al. 1994). Moreover, they are not sensitive enough to detect the thinnest clouds that can be numerous at high altitudes, since the lowest detection limit typically attributed to satellite passive sounders is around 0.1 in terms of optical thickness (Stubenrauch et al. 2006; Wylie et al. 1995). Ground lidars are very efficient tools for getting information about optically thin clouds (Cadet et al. 2005), but their results are restricted to a limited set of locations on the earth’s surface. Moreover, measurements at high altitudes can be significantly affected by lower atmospheric layers (aerosols, clouds).

Spaceborne observations from satellites flying together with complementary instruments—namely, the A-Train—now offer new opportunities to provide an unprecedented survey of cloud properties on a global scale (Stephens et al. 2002) and to compile more reliable representations of clouds to accurately estimate transmittance statistics. Among these satellites, Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations

Corresponding author address: Karine Caillault, Theoretical and Applied Optics Department, Office National d’Études et Recherches Aéronautiques, Chemin de la Hunière et des Joncherettes, BP 80100, 91123 Palaiseau CEDEX, France.

E-mail: karine.caillault@onera.fr

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(CALIPSO), a joint U.S. National Aeronautics and Space Administration (NASA) and French Centre National d’Études Spatiales (CNES) satellite mission, launched in April 2006, is dedicated to the study of aerosols and thin clouds (with a detection limit as low as 0.01 in terms of optical depth) (Winker et al. 2007, 2009, 2010; Hunt et al. 2009; Dupont et al. 2010). The payload includes Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), which delivers, for the first time on a global scale, multiyear measurements of vertical profiles of cloud and aerosol backscattering properties.

The detection performance of a satellite or airborne optronic sensor can vary widely as a function of local meteorology and viewing geometry, and thus transmittance statistics only based on CFLOS may be too restrictive to predict the chance for mission success. Consequently, there is a need to get transmittance statistics. The degree of atmosphere transparency for which a mission is supposed to be successful is given by a transmittance threshold: above this threshold, the atmosphere is considered to be clear enough to obtain good detection performances.

The aim of this study is to determine transmittance statistics for different detection performances scenarios: various LOS configurations are considered with several transmittance thresholds. Seasonal variation is also taken into account, and the assumption of horizontally infinitely wide clouds is tested versus finite length clouds. In this paper, transmittance statistics are calculated using high-cloud optical and geometric properties (called climatology thereafter) obtained from CALIOP data.

The paper is organized as follows. In section 2, the high-cloud occurrence climatology obtained from CALIOP data is presented and the methodology used to calculate transmittance probabilities is described, with the assumption of horizontally infinitely wide cloud at first and then for a cloud with finite horizontal length. Sensor performances calculations are presented in section 3. Two main applications are considered: (i) surveillance mission by an airborne sensor with a close-to-the-horizon viewing angle and also with an oblique viewing angle, and (ii) an optical link between a satellite and an airborne sensor. Finally, concluding remarks are given in section 4.

2. High-altitude cloud occurrence climatology to calculate transmittance probabilities

a. High-altitude cloud occurrence climatology

Long-term global cloud climatologies have been derived from a number of different passive satellite sensors. Data come from, for example, imaging radiometers such as the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites (Ackerman et al. 2008); the International Satellite Cloud Climatology Project (ISCCP) (Rossow and Schiffer 1999), which collects and analyzes radiance measurements from a suite of weather satellites; and the Stratospheric Aerosol and Gas Experiment II (SAGE II) photometer on board the Earth Radiation Budget Satellite (ERBS) (Liao et al. 1995). The main limitations of these instruments are an optical depth detection limit greater than 0.3 that prevents detection of optically thin clouds and the lack of information about cloud bases or multilayered clouds. Infrared vertical sounders such as the Television Infrared Observation Satellite (TIROS-N) Operational Vertical Sounder (TOVS) (Scott et al. 1999) are more sensitive to low optical depth clouds with a detection limit at 0.1 (Stubenrauch et al. 2006; Wylie et al. 1995). This detection limit is still too high to detect subvisible clouds (optical depth < 0.03) and a large part of semitransparent clouds (0.03 < optical depth < 0.3). These cloud classes, defined in Sassen and Cho (1992), are widely used in papers relative to high-cloud studies. However, for the sake of clarity concerning our study, we propose to add a “thick cloud” category with an optical depth between 0.3 and 3. The “opaque” category will only cover clouds with an optical depth higher than 3 for which transmittance is smaller than 0.05. Active optical sensors can reach an optical depth detection limit as low as 0.01 (Davis et al. 2010), and several cloud climatologies from ground lidars have been established over time. These sensors being very sensitive to scattering by ice particles, they show a very high occurrence of subvisible and semitransparent cirrus clouds likely to be underestimated in historical cloud climatologies (Dupont et al. 2010). However, the measurements are local [see Dupont et al. (2010), Noël and Haefelin (2007), and Keckhut et al. (2006) for midlatitude studies; and Comstock et al. (2002) for tropical cases] and affected by the presence of low clouds (Sassen et al. 2008).

With an optical depth detection limit at 0.01 or less with sufficient averaging (Rogers et al. 2011; Winker et al. 2009), a global coverage, and a multiyear collection, CALIOP data have been selected to build the high-clouds climatology required for transmittance statistics calculation. The CALIPSO spacecraft follows a sun-synchronous orbit crossing the equator southward at 0130 and northward at 1330 local standard time, passing in the same track every 16 days (Winker et al. 2009). CALIOP is a two-wavelength depolarization lidar. Detection of cloud (and aerosol) layers primarily relies
on the 532-μm channel (polarized), as it is more sensitive than the 1064-nm channel, and is based on an adaptive threshold detection technique (Vaughan et al. 2009). Vertical resolution is 30 m from 0- to 8.2-km altitude, 60 m from 8.2- to ~20.2-km altitude, and 180 m above 20.2-km altitude. CALIOP level 2 (version 3.01) data products are used in this study (Powell et al. 2011). Cloud properties are obtained from CALIOP cloud layer products at 5-km resolution (L2 5 km). These layer properties specify the spatial and optical characteristics of each feature found and include quantities such as layer base and top altitudes, integrated attenuated backscatter, and optical depth cloud. Comparisons of CALIOP observations with ground-based or airborne lidar measurements show an overall good agreement despite discrepancies in cloud fraction retrieval (Dupont et al. 2010; Thorsen et al. 2011; Yorks et al. 2011). Only layers with high-confidence cloud–aerosol discrimination (CAD) score (Liu et al. 2009) are considered in this study (CAD scores 103, 104, and 105 being rejected). Because of the multiple horizontal averaging resolutions scheme applied to detect layer boundaries in the L2 5-km cloud product (Vaughan et al. 2005), detected cloud layers may overlap. This affects mostly the geometrical thickness and the optical thickness. A correction has been introduced that is applied to the CALIOP data used to build the climatology (Thorsen et al. 2011). We use both CALIOP daytime and nighttime data products from June 2006 to September 2011. The climatology is built on a 3° × 3° horizontal resolution grid with global coverage (latitude 80°N–80°S, longitude 180°W–180°E) and a 2-km vertical resolution. In each mesh grid, cloud occurrences are calculated as a function of cloud altitude, optical depth, and geometric thickness. Only clouds with tops higher than 7 km are taken into account in our climatology, consistent with the surveillance applications we are targeting and the associated viewing conditions. As the CALIOP lidar signal is totally attenuated for cloud optical depth greater than 3 or 4 (Sassen et al. 2008), an underestimation of the number of multilayer clouds may occur in the case of multilayer cloud with a thick upper layer. Use of the combined CloudSat Cloud Profiling Radar (CPR) (Stephens et al. 2002) (not done in this study), also part of the A-Train of formation-flying satellites, and CALIOP data would improve the multilayer detection. Indeed, CloudSat CPR is well suited to give information about thick cloud-top and cloud-base heights.

As an example of our climatology, Fig. 1 shows occurrences of clouds with optical depth higher than 0.3, in the range of cloud top altitudes 11–13 km, in spring, at nighttime.

b. Transmittance probabilities

Statistical evaluation of airborne or satellite sensors’ performances requires transmittance probabilities from high-cloud occurrence climatology. Important assumptions are made for this study: aerosols and molecular extinction are not considered, so that extinction is only due to clouds. Cloud transmittance $T$ along the sensor LOS is given by $T = e^{-\tau}$, where $\tau$ is the cloud optical depth; $\tau$ can be written as $\tau = \sum \sigma_i l_i$, where $i$ is the $i$th crossed cloud layer, $\sigma_i$ is the extinction coefficient of cloud layer $i$, and $l_i$ is the length of the LOS segment crossing cloud layer $i$. The viewing geometry for an airborne sensor at altitude $H$, with viewing angle $\theta$, is given in Fig. 2.

To determine transmittance statistics, one needs to estimate the clouds’ joint probability density $P(x_1, x_2, x_3)$, that is, the probability of cloud presence at altitude $i$, with geometrical thickness $dl$ and optical depth $d\tau$. Its expression is

$$P(x_1, x_2, x_3) = \frac{\sum N(x_1, x_2, x_3)}{N_T},$$

where $x_1$ stands for cloud height, $x_2$ for optical depth, and $x_3$ for geometrical thickness; $N(x_1, x_2, x_3)$ is the number of samplings meeting selected values of $x_1$, $x_2$, and $x_3$; and $N_T$ is the total number of cloudy samplings, whatever the cloud height, optical depth, and geometrical thickness.

As there is no information about cloud length, clouds are considered to be horizontally infinitely wide in a first step, which will be called infinite cloud case.

A more realistic cloud model can be defined using finite rectangles. In that case, cloud horizontal extent is
required. Wood and Field (2011) give near-global cloud horizontal size distributions for the scale range 0.1–8000 km using MODIS data, and observational data are collected using research aircraft and global model data from the Met Office Unified Model. They consider clouds at all altitudes. Dupont (2008) give statistics of high-cloud horizontal extent, established from 4-yr ground-based measurements at the CERES Ocean Validation Experiment (COVE) station (37°N, 75°W): horizontal spatial extent is smaller than 50 km for 39% of high clouds, between 50 and 100 km for 23%, between 100 and 200 km for 16%, and is greater than 200 km for 22%. Despite the lack of representativeness of these statistics at the global scale, we use them to get data to create a finite cloud model. Since these cloud lengths’ statistics relative to high clouds do not depend on cloud altitude, joint probability density, including cloud horizontal length, can be written as

\[ P(x_1, x_2, x_3, x_4) = P(x_1, x_2, x_3) \times P(x_4), \]  

where \( x_4 \) stands for cloud length and

\[ P(x_4) = \frac{\sum N(x_4)}{N_T}. \]

Cloudy scenes are generated by a Monte Carlo method. This model enables one to build scenes containing rectangular infinite or finite clouds, made up of up to three layers. Convergence is ensured thanks to a great number of generated scenes. Random draws are performed to get the cloud layers’ property values (altitude, thickness, and optical depth), which are constrained by joint probability densities calculated from cloud occurrence climatology. It is then easy to put a sensor at any place in the scene and to calculate optical transmission along its line of sight. Around 400 sensor positions are randomly chosen in order to cover the whole geographic area. In the case of finite clouds, additional random draws are performed along the LOS, filling the scene with cloudy- and clear-sky areas in agreement with cloud occurrence climatology and cloud length statistics. For infinite clouds the scene is either totally cloudy or totally clear. Thus, the probability of having a totally cloud-free LOS is higher in the infinite clouds case than in the finite one.

Transmittances are then calculated for lines of sight crossing the scenes. Probability that a \( T \) is greater than a given threshold \( T_t \) is given by

\[ P(T \geq T_t) = \frac{\sum_k (T \geq T_t)}{\sum k}, \]  

where \( k \) stands for the different cloudy scenes’ realizations, \( T \geq T_t \) is equal to 1 when the condition is fulfilled, and 0 otherwise.

Based on the clouds’ joint probability densities [Eq. (1) in the infinite cloud case and Eq. (2) in the finite cloud case], sensor performances expressed as transmittance probabilities [Eq. (3)] can be determined.

3. Sensor performance calculations

Detection performances are estimated for two main applications: (i) a surveillance mission by an airborne electro-optical sensor first with a viewing angle close to the horizon and then with a more oblique viewing angle (in both cases, an air-to-space path is considered, that is, the path ends when the transmission along the path falls to zero) and (ii) an optical link between a satellite and an airborne sensor, in nadir-viewing conditions. More particularly, the geometrical conditions needed to meet the required detection performance conditions are scrutinized.

a. Airborne surveillance sensor

The impact of cloud presence on airborne sensor performance is often translated in terms of CFLOS probabilities higher than a prescribed threshold \( P_T \). This can be written as

\[ P(T = 1) \geq P_T, \]  

FIG. 2. Viewing geometry of an airborne sensor at height \( H \) with viewing angle \( \theta \); \( l \) is the segment of the sensor LOS crossing the cloud layer.
where $P(T = 1)$ is obtained from Eq. (3). In that case, clouds are considered as totally opaque.

Sensor performances are arbitrarily supposed not to be affected by cloud presence if $P_T \geq 0.95$. The lowest limit of the sensor field of view (FOV) $\theta_{\text{min}}$ (see Fig. 2 for description of observation geometry) that will satisfy Eq. (4) with a prescribed $P_T$ value can thus be determined by solving Eq. (4). Cloud layers are supposed to be horizontally infinitely wide in this first step.

This paper focuses on the Mediterranean area, with a spatial domain extending from 17° to 49°N and from 3°W to 45°E. The airborne sensor altitude ranges between 12 and 20 km and the viewing angle ranges from $-2.5^\circ$ below the horizon up to $0^\circ$. To have a global coverage of the zone, many different sensor locations are taken into account. The lowest limit of the sensor FOV ($\theta_{\text{min}}$) as a function of the sensor altitude, for the four seasons, daytime, over the Mediterranean region is displayed on Fig. 3; $\theta_{\text{min}}$ strongly varies with sensor altitude. Best performances are achieved for the highest sensor altitudes. For example, a sensor located at 19-km altitude or above has a probability of having a clear LOS higher than 0.95 whatever the season and LOS elevation angle, provided it is above $-2.5^\circ$. On the other hand, below 13 km only few angles meet the requirements. Seasonal variations of sensor performance are not obvious. A slight performance degradation can be observed in summer in agreement with the summer cloud occurrence above 12 km, which is higher than during the rest of the year.

These results can be compared with sensor performance calculations presented in Chervet and Roblin (2006) over the same area. The authors of this previous study developed an analytical model based on mean cumulative probability distributions of high-altitude cloud occurrences, with some simplifying hypotheses, such as infinite and totally opaque clouds. The cloud climatology considered was obtained from 8 yr of TOVS data (Scott et al. 1999; Stubenrauch et al. 1999) at a spatial resolution on the earth of $1^\circ \times 1^\circ$. A comparison between high-cloud (with a top height above 7 km) occurrences from TOVS data and CALIOP data is shown in Fig. 4, over the Mediterranean area at autumn season by day. CALIOP cloud occurrence cannot
be obtained with a spatial resolution as high as TOVS because of a lower revisit time and a shorter acquisition period. High-cloud occurrence from CALIOP is largely higher than TOVS, which is consistent with optical depth detection limits of each instrument. Mean high-cloud occurrence over the Mediterranean area from the TOVS climatology is close to 20%, while it reaches 30% in the CALIOP case. The lowest limit of the sensor FOV ($\theta_{\text{min}}$) as a function of the sensor altitude obtained from CALIOP cloud occurrence (Fig. 3) can be compared with the one obtained with TOVS cloud occurrence (Fig. 5). It is important to notice that the choice of cloud climatology has an obvious influence on sensor performance calculations. Indeed, sensor performance calculated with CALIOP climatology is worse than the one obtained with the TOVS climatology. This observation is consistent with the lack of optically thin clouds in TOVS climatology, which are included in CALIOP climatology. In summer, for a sensor altitude of 13 km, $\theta_{\text{min}}$ was evaluated to $-1.6^\circ$ with TOVS climatology against $-0.75^\circ$ with CALIOP climatology. The only season when results obtained with both methods are very close is spring. At this time of year, clouds with tops higher than 12 km altitude are very numerous in TOVS climatology compared to the other seasons. Their occurrence reaches 6%, for a total cloud amount around 19%, against 3% in autumn, for a total cloud amount of 13%. Seasonal variations of sensor performance are less pronounced with the CALIOP climatology. For example, for a sensor at 14-km altitude, $\theta_{\text{min}}$ ranges from $-1^\circ$ to $-1.9^\circ$ throughout the year with TOVS climatology and from $-1^\circ$ to $-1.25^\circ$ with CALIOP climatology.

To improve sensor performance estimation, more realistic finite rectangular clouds are taken into account. Transmittance statistics are computed considering the clouds’ joint probability density $P(x_1, x_2, x_3, x_4)$ defined in Eq. (2). Sensor performance in terms of the lowest limit of the sensor FOV as a function of the sensor altitude is shown in Fig. 6. Generally, performance appears to be slightly worse than for infinite clouds except in summer, when it is largely degraded. The performance degradation is in agreement with the lower probability of having a cloud-free LOS in the finite case compared to the infinite one. This trend is emphasized.
in summer when, as mentioned previously, the occurrence of clouds above 12 km from CALIOP climatology is more prominent than during the rest of the year (not shown).

To be less restrictive, instead of evaluating CFLOS probabilities \([T_t = 1 \text{ in Eq. (3)}]\), \(T_t\) can be lowered. A threshold \(T_t = 0.8\) has been chosen to calculate new sensor performance estimations. As previously, the lowest limit of the sensor FOV as a function of the sensor altitude is shown in Fig. 7 in the case of infinite cloud and in Fig. 8 in the case of finite cloud. In both cases, performances reached with the new threshold are very close to those obtained with \(T_t = 1\). This trend can be understood by scrutinizing Fig. 9 showing histograms of transmittances values computed from the airborne surveillance sensor scenario, that is, sensor altitude between 12 and 20 km and viewing angle from \(-2.5^\circ\) to \(0^\circ\). It can be noticed that most of the transmittances values are close to 0 (opaque cloud layer) or equal to 1 (cloud-free case). It is consistent with the close-to-the-horizon viewing conditions that lead to a large optical path inside the cloud and thus to a strong decrease in transmittance as soon as a cloud is met along the LOS. The great number of close-to-one transmittance values is in agreement with the high-cloud cover statistics estimated around only 30% at global scale with pronounced latitudinal variability ranging from 20% at midlatitudes to more than 40% in the tropics (Stubenrauch et al. 2006; Sassen et al. 2008). An improvement of performance can be observed between calculations with \(T_t = 1\) and \(T_t = 0.8\) in summer in the finite cloud case, since the number of thin clouds is higher in summer than for the other seasons.

In summary, the performance of an airborne sensor with viewing angles close to the horizon can be estimated using the assumption of an infinitely wide and totally opaque cloud. The use of a more sophisticated model with finite and nonopaque clouds does not change performance calculations a lot.

If we consider a wider viewing angle, then the impact of the finite or infinite cloud model is more significant, as can be observed in Fig. 10. The probability that the transmittance along the LOS is higher than a chosen
threshold $T_t$ is plotted relative to the threshold for the four seasons in the infinite and finite cloud cases. The sensor altitude is 20 km and the viewing angle is $\theta = -20^\circ$. Transmittance probabilities are given for the Mediterranean area, by day for the four seasons in the infinite and finite cloud cases. Legend labels indicate season (W: winter, Sp: spring, Su: summer, A: autumn) and infinite (I) and finite (F) cloud cases.

b. Optical link between a satellite and an airborne sensor

Characterization of an optical link between a satellite and an airborne sensor requires prediction of transmittance values. The model proposed in this paper is used to perform transmittance computations between a 600-km-altitude nadir-viewing satellite and an aircraft. The viewing geometry is given in Fig. 11. The probability that the transmittance along the LOS is higher than a chosen threshold $T_t$ is calculated for six aircraft altitudes ranging between 9 and 14 km. Results are shown in Fig. 12 for the four seasons, with the finite cloud model and over the Mediterranean area. Generally, transmittance probabilities obtained in winter, autumn, and spring are very close. As in the previous case, they are higher in summer for the lowest aircraft altitudes because occurrences of clouds between 8 and 12 km are lower in this season. Probabilities of transmittance higher than $T_t$ evenly decrease with the threshold. Nevertheless, occurrences of transmittances calculated with $T_t = 0.8$ are always above 0.9 whatever the season or the sensor altitude. If we suppose that the optical link is not affected by cloud presence as soon as $P(T \geq 0.8) \geq 0.95$, then the aircraft has to be located above 10-km altitude in spring, autumn, or winter. In summer, whole altitudes present satisfactory performance. The threshold parameter and transmittance probability have been arbitrarily chosen. They have to be adapted in relation to expected applications. It should be interesting to repeat this study at different geographical locations in order to define the most promising area for airborne satellite optical link characterization.

4. Conclusions

To evaluate airborne sensor performance, transmittance statistics along the sensor LOS have been calculated based on a probabilistic approach. The impact of cloud presence along the LOS was determined using
a cloud climatologic dataset. It was built from CALIOP cloud products, restricted to high clouds only. The detection limit of the CALIOP instrument allows the inclusion of nonopaque clouds, which were not previously taken into account in sensor performance studies. Different observation geometries have been considered in order to demonstrate the potential of the proposed method for various applications. In particular, close-to-the-horizon and oblique lines of sight were defined for airborne surveillance application and nadir LOS was chosen in the case of an optical link between a satellite and an airborne sensor. Results showed that assumption of horizontally infinitely wide opaque clouds is justified in the case of close-to-the-horizon lines of sight. In regard to the other observation geometries, introduction of nonopaque clouds and a more realistic cloud model with a finite horizontal length may have a strong effect on performance estimation. Such a study about the impact of nonopaque finite clouds on airborne sensor performance was never presented before.

It has been shown in this work that seasonal variation of cloud occurrence affect sensor detection performance. Clouds occurrences are also strongly dependent on geographical location as well as cloud horizontal extent. Sensor performance is thus related to the sensor location. In the future, it will be interesting to study this geographical dependence in combination with seasonal variation in order to determine the best locations to
place a sensor on the globe or the zones to be avoided. Statistics of cloud length, restricted to a small area in this study, would give more precise transmittance estimations and thus more precise performance evaluations. Finally, the extension of the climatologic dataset by including aerosols is also an important point to consider, since aerosols may have a nonnegligible impact on transmittance.

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