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A Stereoscopic Approach for Cloud Base Height Assessment Over an Optical Ground Station

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ABSTRACT

Telecommunication and remote sensing data exchanged between Earth and space has increased dramatically in recent years. Radio frequencies, the medium used for several decades has shown to reach its capacity. Free space optical communications, achieved with laser transmitter devices, is an alternative with better transmission rate and increased security. However, a major drawback of this technology is that laser signal cannot cross through thick clouds, which imply to set up a network of optical ground stations with handover management strategies based on Cloud Optical Depth (COD) observation and Cloud Motion forecasts. Ground-based long-wave infrared observations from a sky imager can be used to estimate COD. However, as a low thin cloud may have similar thermal signature than a high thick cloud, additional Cloud Base Height (CBH) measurement is needed to retrieve accurate COD in any weather situation [1]. The CCSDS currently recommends to use a ceilometer for this purpose [2]. Here, we explore an alternative approach, retrieving CBH directly from a pair of thermal sky imagers and stereoscopic methods. Our CBH retrievals have been compared with the measurement of a reference ceilometer. The results showed a good agreement for a continuous period of acquisition over several days, with a Root Mean Squared Error of 15%. In addition, stereoscopy offers a wider field of view and thus, may increase the forecasting horizon and accuracy, compared to a sky imager+ceilometer configuration [3] [4] [5]. We believe this approach is promising for the cloud monitoring of Optical Ground Stations and should be further investigated.

Keywords: Stereoscopy, thermal infrared imagery, cloud base height

1. INTRODUCTION

Considering the ever-growing volume of data acquired and transmitted by satellites, having a good enough space-to-ground data transfer capacity constitutes a major challenge to provide a fitted broadcast service. Optical communication technologies offer several advantages compared to the more conventional radio communications. They allow higher throughput and increased confidentiality without encroaching on the already saturated radio spectrum. However, these systems are vulnerable to atmospheric turbulence and even more to cloud cover, which can completely break the transmission of the laser through the atmosphere. To guarantee a continuous availability of the system, it is necessary to work with networks of optical ground stations (OGS), optimally dispatched in order to keep at least one station under clear sky conditions [6]. With an additional cloud motion forecast functionality, it is possible to anticipate cloud obstructions and trigger OGS handovers to prevent network interruptions. However, handovers are risky manoeuvres that can themselves lead to connection issues that should be avoided as much as possible. The estimation and forecast of cloud optical depth (COD) constitutes a way to minimise their occurrences, considering that a cloud with a sufficiently low COD does not necessarily block the laser signal.

Sky imagers are considered to be the most valuable tools to monitor and forecast the cloud cover at high spatial and temporal resolutions from 1 minute up to 30 minutes ahead [7]. For the day and night surveillance of a free space optical communication system, the use of thermal infrared sensors is required [8] [9]. There is however an ambiguity between COD and cloud base height (CBH) inherent to these sensors [1]. A high-level cloud with high COD can present the same level of luminance that a low-level cloud with low COD. Therefore, knowing the CBH with high-accuracy significantly increases the quality of the COD estimation. Accurate CBH estimations can be achieved using several sky imagers associated to a stereoscopic reconstruction method, leading to improved overall forecasts [3] [4] [5].

2. STATE OF THE ART

Several methods exist to derive cloud base height from images provided from a pair of wide-angle sky cameras. A first method consists in projecting the image pixels on a georeferenced grid at several heights to find the optimal value that maximises the similarity of the two projected images [3]. A second approach is based on the determination of matching points on the epipolar lines between the two cameras [3]. Finally, the last method involves voxel carving techniques [10] [11]. Voxels (e.g., 3D pixels) located in the azimuth and zenith direction of a cloudy image pixel are marked in the 3D space. Voxels marked twice (or more, if there are more than two cameras) have a high probability of containing clouds and can therefore be localized. All these approaches have been tested on visible cameras only. Nevertheless, the feasibility of stereoscopic measurements using two thermal cameras has been demonstrated for other applications [9]. In this paper, a CBH estimation methods developed by Nguyen [3] is applied on images acquired by a pair of Sky InSight™ (a thermal-infrared sky imager designed by Reuniwatt) and the results are compared to the CBH measures acquired by a CL51 Vaisala ceilometer located at Onera-Toulouse.

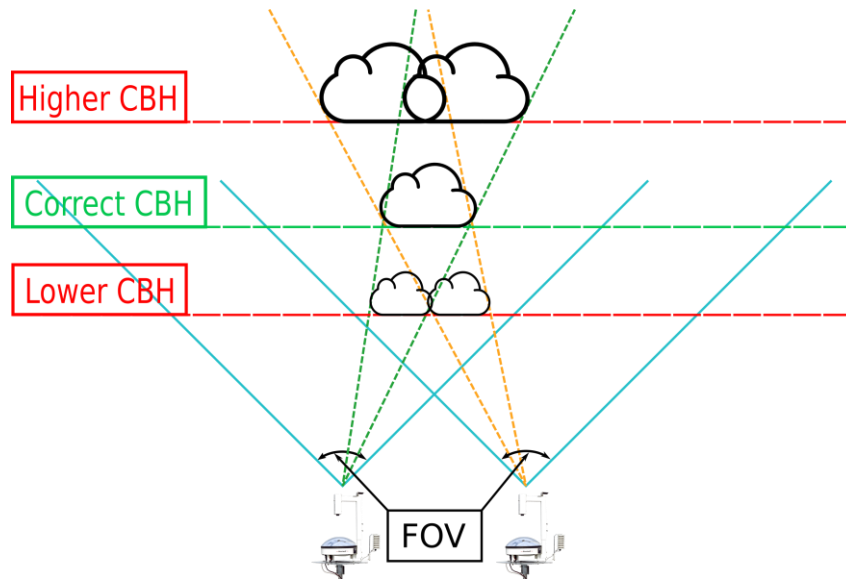


Figure 1. CBH processing by projection of the pixels on a georeferenced grid and maximisation of the similarity of the two projected images (FOV means Field Of View)

3. METHODOLOGY

A sky imager only provides the angular position of a given cloud. To locate it geographically, it is necessary to know its CBH. Here, each pixel of the two cameras is projected on a common geographic grid, considering that all clouds are characterised by the same CBH. For a range of several assumed CBH, the nRMSE (Normalised Root Mean Squared Error) values between the two projections are calculated and the CBH for which this error is minimal is kept as the true CBH value (cf. Figure 1). The geographical grid covers an area of 12kmx12km centred on the barycentre of the two cameras. The points corresponding to a zenith angle greater than 85° are ignored in the calculation. To compare the projection of the two visible cameras, Nguyen uses RGB (Red Green Blue) saturation values for the first camera, and a cloud segmentation mask for the other one. For the Sky InSight™, which is sensitive to the thermal infrared band, we worked directly with normalised radiance.

4. INSTRUMENTS AND DATASETS

Two observation stations are used in the context of this study (cf. Figure 2). These stations have been designed and set up by the IRT Saint-Exupery as part of the ALBS project. The first one (Site 1) is located in Toulouse at the Airbus Defence & Space site and is composed of several instruments:

- Two infrared pyrometers, one pointing to the zenith and the other one to the horizon,

- A wide-angle camera operating in the visible part of the spectrum (SkyCam Vision™),
- A wide-angle camera operating in the thermal infrared part of the spectrum (Sky InSight™),
- A pyrheliometer mounted on a solar tracker.

The second station (Site 2) is located approximately one kilometre northwest of the first one and consists of a single Sky InSight™. A Sky InSight™ is a sky imager composed of a thermal-infrared camera (8-14μm) aiming downward at a chrome-coated hemispheric mirror, which allows it to provide sky images with a field of view (FOV) of 180° and a temporal frequency of 30 seconds. The input of the algorithm detailed in the next section consists in a pair of sky images acquired at the same time by the two Sky InSight™ imagers. Both of them are first of all geometrically calibrated in order to associate an azimuth angle and a zenithal angle to each pixel. This is done using a history of the sun's positions over time, as detected on the images and modelled by the SOLPOS 2 NREL model mentioned in Liandrat et al. [12]. In the end, the results are validated by comparison with a reference CBH value acquired by a CL51 Vaisala ceilometer located on the Onera site [13] [14], 1.5 kilometres northwest of the two sky imagers. Both Sky InSight™ and reference data have been continuously acquired during a whole week in October 2020.

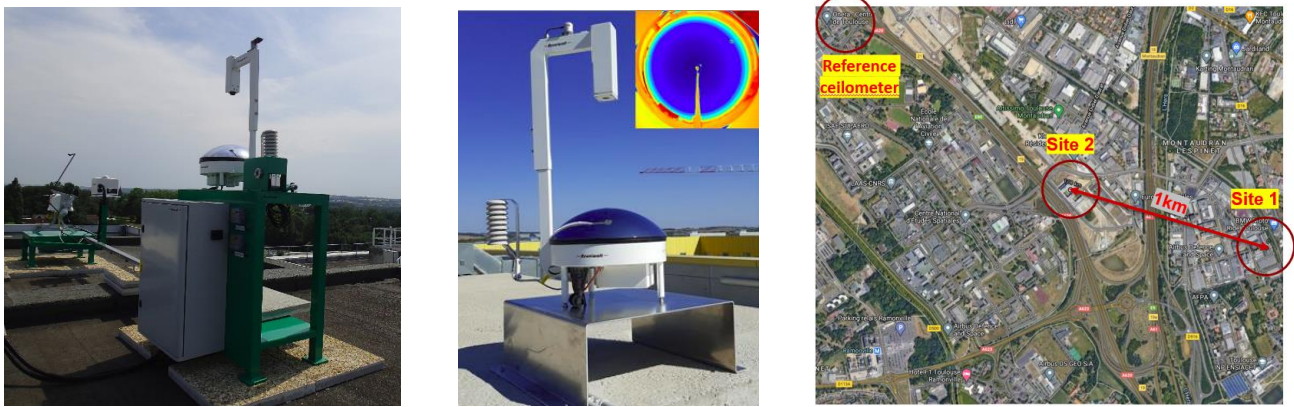


Figure 2. The Sky InSight™ on the two observation stations, Site 1 on the left and Site 2 on the middle. Relative positions of the two test benches and the reference ceilometer are defined by the map on the right.

5. RESULTS

Figure 3 shows an example of the evolution of the nRMSE between the projected images as a function of the CBH. The plot exhibits a clear minimum for a CBH of 1400 meters which is quite consistent with the ceilometer measurement, indicating a cloud base height of 1463 meters. The resulting projections of the two cameras are visually quite similar.

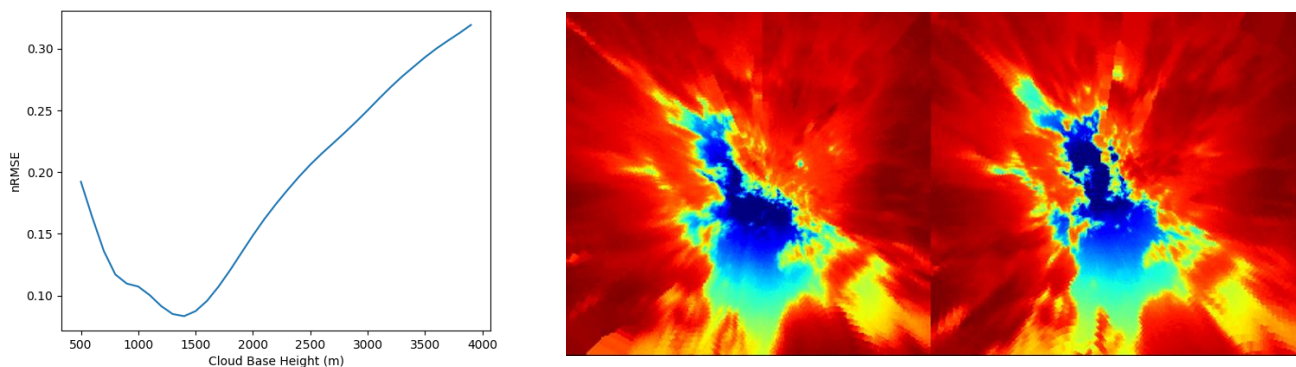


Figure 3. For a specific timestamp (7th of October 2020, 11h04 UTC), evolution of the nRMSE between the projected images as a function of the CBH on the right and sky projection of the view of the two cameras for an optimal CBH hypothesis of 1400m on the left.

An overall good correlation has been observed between the ceilometer and the Sky InSight™ outputs on a first test period of 14 hours, with a nRMSE of 0,154. Consistent with the fact that the approach assumes a single-cloud ceiling over the entire image, the accuracy of the CBH is notably good in the presence of a single, scattered layer of clouds (cf. Figure 4). Nevertheless, discrepancies have been observed when two or more layers of clouds are seen in the field of view of the cameras. In this case, several minimums or sometimes no clear minimum appear in the nRMSE curve. The discrepancy between the instruments' field of view is an additional challenge for a comprehensive comparative study. Moreover, a layer of clouds with a gap at Nadir may not be seen by the ceilometer while covering most of the Sky InSight™'s field of view. Further data filtering is required to completely address the limits of the CBH retrieval method.

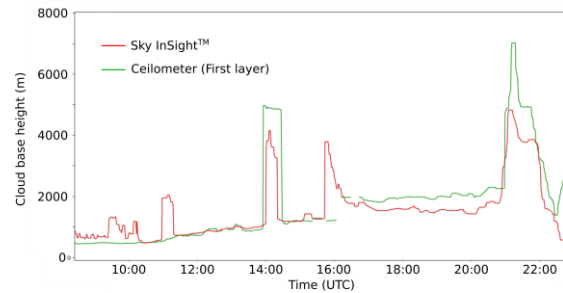


Figure 4. Comparison between the Sky InSight CBH and the ceilometer's first layer CBH with a 10-min median filter

6. CONCLUSIONS

In this work, a stereoscopic projection method initially developed for a pair of visible sky imagers is adapted to Sky InSight™ thermal-infrared imagers. Preliminary results show promises for the monitoring and forecasting of cloud cover to improve the availability of laser optical communication systems, as night monitoring can only rely on thermal imaging observations. A more extensive study is necessary to consolidate these first promising results. Other state-of-the-art methods, such as voxel carving, could be implemented. The question of system optimal layout also seems crucial as the distance between the cameras and the resolution of the images will determine the quality of the CBH restitution of the system, as well as its predictive capability [8]. Understanding the current limitations of our setup will allow us to better address the challenges of future OGS.

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