# An Infrared Cloud Imaging System for Satellite-Earth Laser Communications

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**Abstract.** This paper designs an infrared cloud imaging system for satellite-to-earth laser communications. The imaging system provides a reliable service for establishing an effective satellite laser communication link by collecting the cloud images over a ground station site, processing and analyzing the time and space statistics of the cloud, and acquiring the optical depth of the cloud. To realize day and night automatic monitoring of cloud state information, the infrared cloud imager designed in this paper can effectively observe the fixed viewpoint of the sky, and the uncooled infrared focal plane array calibration model considering the working temperature effect of the detector can meet the radiation setting of sky cloud monitoring, which provides cloud state data information with higher temporal and spatial resolution. Preliminary observation experiments show that the infrared cloud imaging system proposed in this paper can get required real-time cloud image and information for space-terrestrial laser communications.

**Keywords:** Satellite-to-Earth laser communication · High-Rate-Data · Cloud infrared imager · Radiation calibration

## 1 Introduction

With the increasing demand for space data communication, the microwave communication technology used between traditional satellites and grounds has been difficult to meet the increasing data transmission requirements due to the relatively lower transmission rate. The use of laser communication technology have becoming the future development trend of communication between satellites and grounds [1].

There are many factors that need to be considered in the process of building a satellite-earth laser link, including clouds, atmospheric attenuation, atmospheric turbulence, etc., where cloud coverage is one of the key factors that affect the performance of the link or even the broken link. In recent years, scientists from various countries have made many efforts to study the characteristics of clouds, and have conducted corresponding studies using various observation methods, including satellites, ground radiation, lidar, ground imagers and infrared cloud imaging [2–6]. The ideal instrument for measuring cloud characteristics requires to provide continuous day and night cloud image spatiotemporal data, with high spatial resolution and temporal resolution. Although there are many ways to detect cloud coverage, most of the current methods are designed for specific needs and cannot fully meet the requirements of satellite-to-earth laser communication

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applications. The spatial and temporal resolution of satellite observation is limited; lidar is mainly used for fixed-point zenith direction observation; visible light imaging is not suitable for night observation; artificial observation is influenced by empiricism and subjective judgment. Since the clouds have the same infrared radiation characteristics in the infrared (8–14 μm) band regardless of day or night, it is possible to consider using infrared imagers to continuously observe the sky day and night [7].

The attenuation of optical signals by clouds varies greatly with the optical properties of the clouds. The thick cloud layer attenuates the laser signal strong enough to completely cut off the laser communication link. Optical thin clouds, especially cirrus clouds, mainly eliminate the energy of the signal propagation path and reduce the signal quality by scattering and attenuating the light beam. In order to make the satellite-earth laser communication link feasible and reliable, it is necessary to accurately measure the presence or absence of clouds and their optical characteristics between the links. Especially when the satellite has several ground stations as candidates to establish a satellite-earth laser link for communication, the appropriate ground station can be selected based on the observed real-time cloud status information over the candidate ground station, or even predicting the cloud change trend in advance Perform chain building.

Therefore, in order to guarantee the uninterrupted laser communication mission of the satellite and earth, it is very important to obtain the changing trend of the cloud clusters above the ground station in advance, which can be realized mainly through two aspects of work. The first part is to observe the cloud image above the ground station to obtain the optical characteristics of the cloud. The second part is to use machine learning and other technologies and a large number of spatial-temporal data of the cloud map over the ground station to predict the cloud state over the ground station to achieve to predict in advance and actively switch the purpose of the communication link. This paper focuses on the construction of the first part. Since the actual operation of laser communication ground stations requires the use of miniaturized, day and night observation, high spatial and temporal resolution instruments [8] to describe the characteristics of clouds, this paper developed an infrared cloud imager for continuous day and night ground measurement of cloud Statistical characteristics.

## 2 System Design of Infrared Cloud Imager

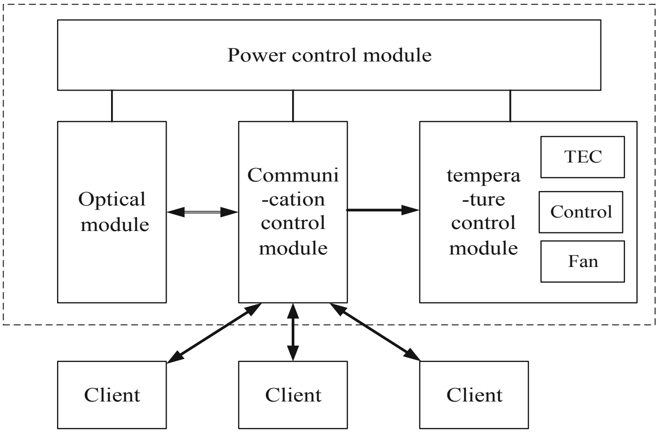
The prototype of the infrared cloud imager designed in this paper is mainly composed of optical module, temperature control module, communication master control module and power supply module. Its main structural diagram is shown in Fig. 1. Use a microcomputer to control the uncooled infrared camera to obtain sky radiation data, and obtain the real-time working temperature information of the imager through the temperature sensor for calibration processing, so as to obtain the infrared radiation distribution cloud image of the sky. After further processing, the required cloud statistical characteristics can be obtained. Cloud statistics based on real-time data can be used in the neural network model training set to predict cloud state information and cloud variation trends.

### 2.1 Optical Module

In the infrared cloud imager designed in this paper, the role of the optical module is to collect the infrared images of the sky. Its core is a microwave radiant heat engine camera based on FLIR TAU2, which can provide a diagonal field of view of 110°. The camera uses a sealed housing design, an uncooled focal plane array, no need for an external thermoelectric cooler, internal heaters and related control circuits, an embedded fan to ensure internal air circulation, and the camera's spectral response is between 8 μm and 14 μm.

The ground station of laser link is usually established at a high altitude, and its temperature difference between day and night is relatively large. The operating temperature range of this camera reaches −40 °C – + 80 °C, which meets the temperature requirements of the actual working scene. However, since it is an uncooled focal plane array camera, its response will drift with temperature, and the camera response needs to be corrected. The specific correction method is shown in Sect.2.

(a) the infrared cloud imager.



(b) Block diagram for the structure of the infrared cloud imager.

**Fig. 1.** Infrared cloud imager.

### 2.2 Temperature Control Module

In order to ensure the imager can work effectively for a long time, a temperature control module is designed to stabilize the temperature inside the imager chassis and prevent instrument failure caused by excessive temperature. The temperature control module is mainly composed of semiconductor (TEC) refrigerator, temperature controller and fan.

Using the temperature sensor inside the camera, the real-time temperature information of the camera is read from the camera serial port through the microcomputer. When the temperature of the camera reaches a predetermined upper threshold, the temperature controller will automatically activate the TEC cooler built in the chassis to cool the interior of the chassis, and use the fan to maintain the air circulation inside the chassis to keep the camera temperature at about 25 °C. The acquired real-time temperature information also supports the camera's radiation calibration.

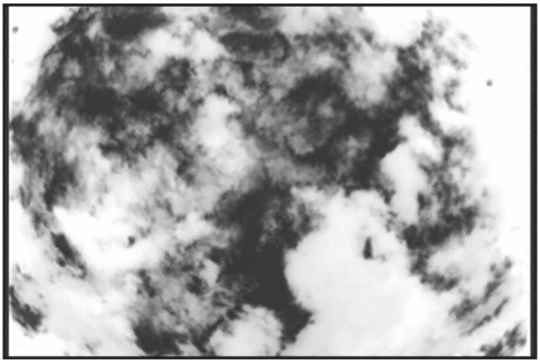
### 2.3 Communication Control Module

The main function of the communication control module is to manage the normal operation of the imager and as an interface for interconnection with users.

Infrared cloud imager integrates a microcomputer to control and access to data. Using the server-client mode, it can accommodate multiple users to access the server and download real-time data at the same time. Users can set the time to take cloud pictures according to their own needs at intervals and send the captured observation data in 8-bit PNG format to the local client via the server. Figure 2 is a typical cloud image obtained by the infrared imager during the day (a) and night (b) obtained by the client.

## 3 Radiation Calibration Treatment

Radiation calibration is the process of converting the brightness gray value of the image acquired by the sensor into absolute radiation brightness. In the infrared cloud imager designed in this paper, because the optical module uses a camera based on an uncooled focal plane array, although it has the advantages of miniaturization, low cost, and fast response, its response is not only dependent on the source radiation or temperature, but also affected by the temperature of the focal plane array and the ambient temperature. Therefore, the radiometric calibration needs to establish a relationship between the output of the camera and the temperature radiation of the scene source, and relies on compensation for this, otherwise the camera cannot maintain stable radiometric calibration.



(a)

(b)

**Fig. 2.** Observations on 27 March 2019.

Figure 3 shows the processing of radiometric calibration. First, the scene image and the focal plane array temperature at the time of shooting are obtained, and the corresponding output when the camera is stabilized at the reference temperature is obtained by using the calibration coefficient that eliminates the dependence of the focal plane array temperature. Finally, the gain and offset measured at the reference temperature are used to convert the FPA stable data into the required comprehensive radiation value [9].

To verify the temperature dependence of the microwave bolometer camera, we placed a FLIR TAU2 camera and a face black body source in an environmental cavity.

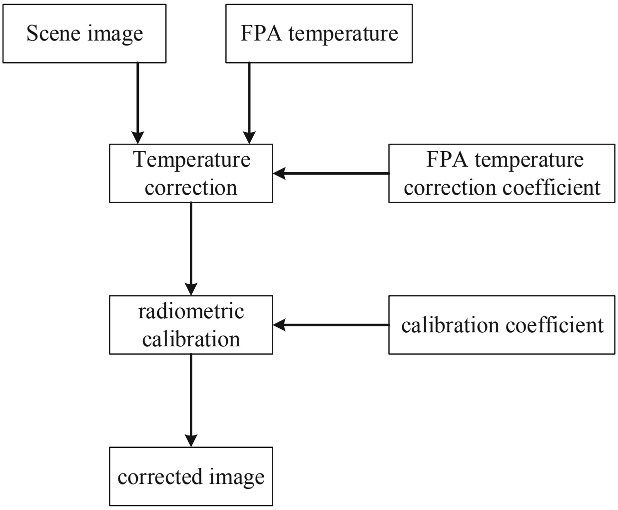


**Fig. 3.** Flow chart of the radiation calibration.

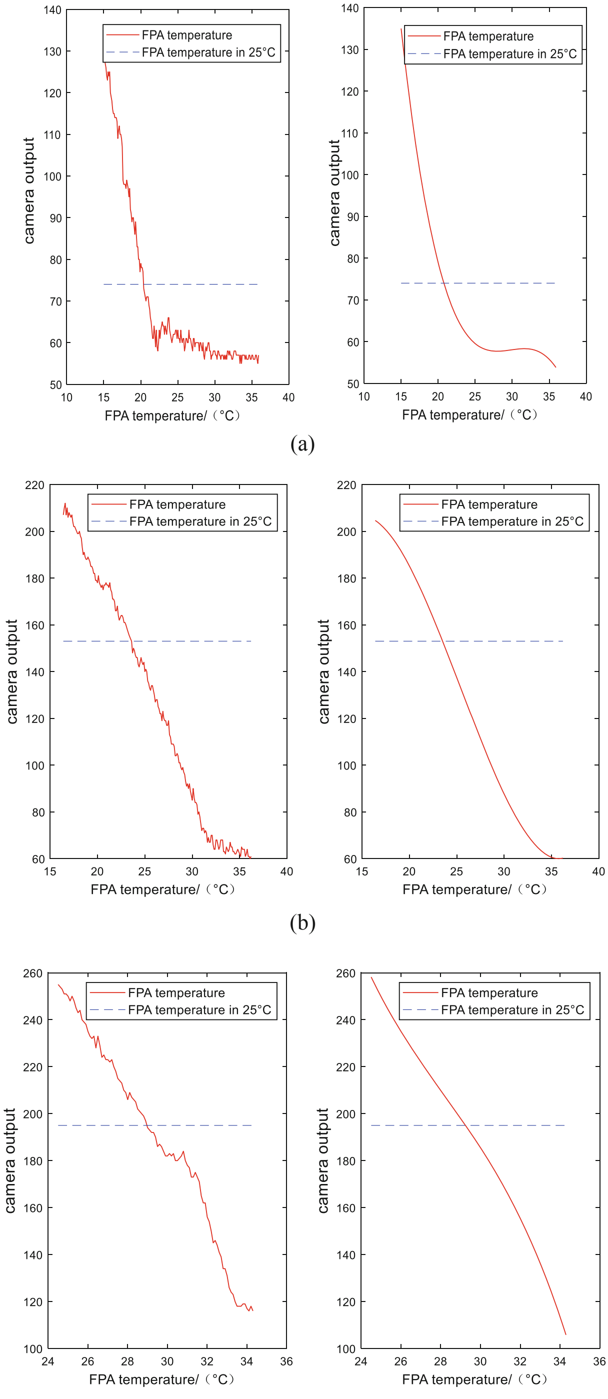
The temperature in the environmental cavity rose from 15 °C to 35 °C, and the temperature of the black body was maintained at 10 °C, 20 °C, and 30 °C, respectively. The results are shown in Fig. 4. In Fig. 4(a)–Fig. 4(c), the left graph is the actual temperature corresponding to the DN value of the camera response output, and the right graph is performed 3 times.

The result after fitting. The red line represents the camera's response to the blackbody source as the ambient temperature gradually increases. The blue line represents the camera response at different blackbody temperatures when the ambient temperature is stable at 25 °C. It can be seen that for this camera, as the focal plane array (FPA) temperature increases, the response to the blackbody scene decreases.

In order to correct the uncooled infrared camera, many patent documents have proposed a variety of calibration methods for thermally unstable cameras. For example, a fourth-order polynomial curve fitting method is used; by changing the camera integration time, reading bias, or other camera parameters to compensate for the corresponding response change of the sensor caused by the temperature change of the focal plane array [10]. The temperature dependence method of the modified focal plane array used in this paper is a correction method based on mathematical principles proposed by P.W. Nugent and J.A. shaw et al. [11]. Mathematical modeling is used to determine the parameters needed to stabilize the camera output when the camera temperature changes.

In this method, the corrected camera response output is mainly determined by two factors, one is the original response output containing the error, and the other is the difference between the current focal plane array temperature ( the reference temperature The center of the range, this article is 25 °C). The camera's output response can be expressed as:

$$D_N = G(T)L_t + B(T) \tag{1}$$



(a)

(b)

(c)

**Fig. 4.** The relationship between the camera's output response and ambient temperature changes. (a.blackbody temperature in 10 °C; b.blackbodytemperature in 20 °C ; c.blackbody temperature in 30 °C) (Color figure online)

Where *G(T)* is the temperature-dependent gain, Lt is the scene radiation, and *B(T)* is the temperature-dependent offset. The temperature correction equation of the camera is:

$$D_{Nc} = \frac{D_N - b(\Delta T)}{1 + m(\Delta T)} \tag{2}$$

Where $D_{Nc}$ is the output value of the temperature correction of the focal plane array, $\Delta T$ is the difference between the FPA temperature and the reference temperature of 25 °C, *b (*$\Delta T$*)* is the temperature-related deviation correction, which is described as a polynomial function with three temperatures condition and a constant bias.

$$b(\Delta T) = b_1 \Delta T + b_s \Delta T^2 + b_s \Delta T^3 - o_1 \tag{3}$$

m($\Delta$T)is the temperature-dependent gain correction, which is described as a scalar multiplied by FPA temperature difference.

$$m(\Delta T) = m_1 \Delta T \tag{4}$$

Among them, m1 is a scalar corresponding to each camera. Then the relationship between the modified DN value and the scene radiation value is:

$$L_{sky} = g\left[\frac{D_N - b_1 \Delta T - b_s \Delta T^2 - b_s \Delta T^3 + o_1}{1 + m_1 \Delta T}\right] + b \tag{5}$$

Through the experimentally collected focal plane array temperature and corresponding camera output, the parameters of the camera used in this paper were subjected to Moore-Penrose pseudo-inversion [10]. Each pixel has a corresponding set of parameters for correction.

The data before and after correction of the focal plane array temperature (black) and the data after correction (red) are shown in Fig. 5. The blue dotted line is the output response when the camera focal plane array temperature stabilizes at 25 °C. The calibrated camera response reduces the relative error of the radiation output of the scene source to about 5%. Using the camera output response after eliminating the temperature dependence of the focal plane array, the radiation calibration of the uncooled infrared camera can be determined.

## 4 Data Processing

The cloud optical depth algorithm uses the atmospheric transmission model to calculate the total radiation value of the atmospheric path in the infrared band from 7.5 μm to 13.5 μm from the cloud height to the ground and the average transmittance of the atmosphere. Use formula:

$$\varepsilon = \frac{L_{cld} - L_a}{\tau L_{bb}} \tag{6}$$

Able to calculate the emissivity of the cloud. Where ε is the emissivity of the cloud, $L_{cld}$ is the cloud radiation value acquired by the infrared cloud imager, $L_a$ is the total

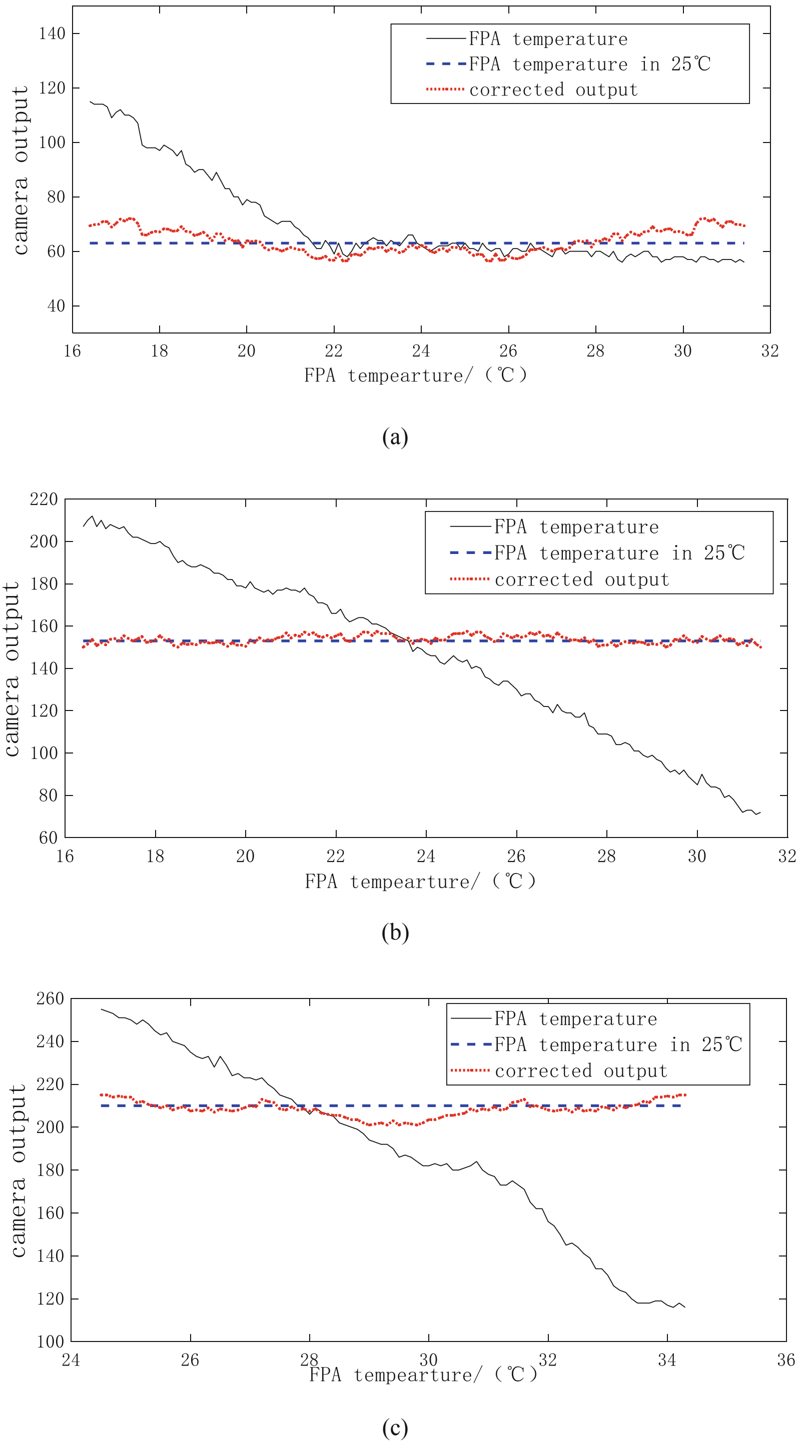


**Fig. 5.** Corrected camera output response at different blackbody temperatures (Color figure online)

radiation value under the local atmospheric path, $\tau$ is the average transmittance under the atmospheric path, and $L_{bb}$ is at the same temperature The radiation value of the black body.

According to the relationship between cloud emissivity and optical depth [12]:

$$\sigma = \frac{\ln(1-\varepsilon)}{-0.79} \tag{7}$$

Finally, an optical depth image of the cloud can be obtained (see Fig. 6).

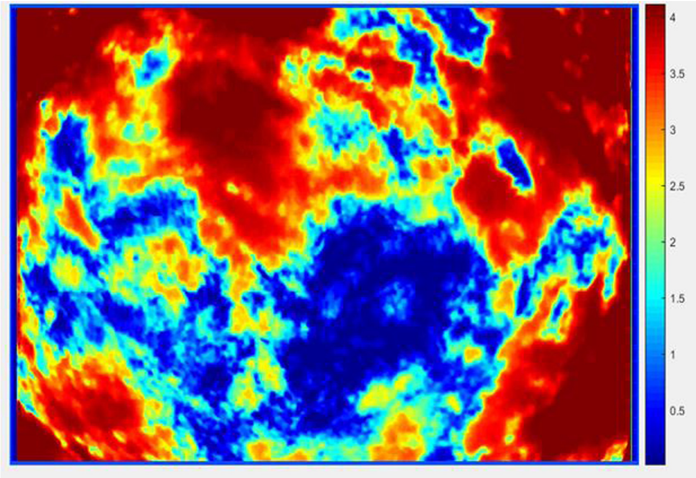


**Fig. 6.** Optical depth image of the cloud.

## 5 Conclusion

In this paper, the calibration model of the uncooled infrared focal plane array is determined to determine its calibration model, which solves the problem of radiation calibration measurement, analyzes how to obtain the optical depth image of the cloud, and on this basis, a ground-based remote sensing for cloud is developed. The infrared cloud imager realizes continuous day and night observation of clouds, and provides a means for obtaining objective and quantitative cloud observation data.

Over the designated area in Nanjing, infrared cloud imager observation is continuing, and quasi-continuous data has been obtained in recent months. A series of studies on the hardware of observation instruments and the characteristics of clouds are constantly being updated and improved. Analysis and processing of the already acquired sky radiation observation data, and further acquisition of cloud cover and cloud height are also in progress.

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