A REMOTE SENSING SATELLITE LIGHTING DETECTION SYSTEM WITH HIGH DETECTION RATE AND LOW COMPLEXITY

Yukun Guo, Na Yin, Wenbo Wu, Jing Huang, Qingyuan Wang

Beijing Institute of Space Mechanics Electricity, Beijing, China - sandra0507@sina.com

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ABSTRACT:

A payload was designed and implemented to do real-time and continuous lightning detection which can be used on remote sensing satellite. The payload consists of sensor unit and electronics unit. Based on the analysis of lighting signal spectral characteristics, the sensor unit adopts ultra-narrowband filtering technology to realize lightning signal spectral filtering, and uses high frame rate area array CMOS device as photosensitive element to obtain image information. In order to reduce the complexity and hardware resources of the electronics unit, a continuous mean elimination method is used to detect lightning signals according to the instantaneous characteristics of lightning. The self-adaptive double threshold recognition method is utilized to detect the recognized lightning signal, which significantly reduces the detection time with a detection rate up to 95%. The electronics unit has the function of quick adjustment of detection threshold through instruction, which provides a more flexible application space for lightning characteristics analysis on the ground. In addition, the system can be used to detect other point or surface target by the change of optical design according to the different characteristics of the detection target, such as the large-scale fire disaster or military target.

1. INTRODUCTION

1.1 Characteristics of lightning

It is found that lightning is closely related to severe convective weather phenomena such as thunderstorms. So the distribution, change and location of severe convective weather such as thunderstorms can be obtained by detecting lightning. Lightning can also predict the formation of tornadoes, because each tornado is formed in an unusually strong thunderstorm. Before a tornado forms, lightning flashes in a particular unit of a thunderstorm have a unique "jumping characteristic". If the jump signal can be detected in real time, tornado warnings can be issued earlier and more accurately. Generally said lightning can be divided into "cloud flash" and "ground flash". Because the cloud flash can form a number of high temperature and high heat discharge channels in the atmosphere, the lightning generated instantaneous strong current can move back and forth rapidly in this discharge circuit, higher than the conventional ground flash frequency, so the frequent flash potential is formed. Intra-cloud lightning (cloud flash) is one of the most frequent lightning events in nature, generally accounting for more than 60 percent of the global lightning population. The in-cloud lightning and cloud-to-ground lightning observed from space can more accurately reflect the frequency of lightning flashes. Therefore, through the observation of lightning by remote sensing satellites in geostationary orbit, covering a range of observed cloud flash and ground flash at the same time, and the remote sensing data can be used to provide more reliable and timely tornado explosive, in order to improve air traffic flow management, and provides the climatology data, which can let the earth climate change to be known.

1.2 Domestic and international research

The USA, whose depth and degree of research leading the world, had become the first in terms of the research and detection of lightning phenomena. However, the earliest LIS and ODT launched by the USA were both polar-orbiting satellites. The GOES-R geostationary orbit weather satellite launched by NASA in 2016 is equipped with the lightning detector GLM (Geostationary Lightning Mapper), which achieves high temporal resolution and detection efficiency of lightning detection in geostationary orbit. And currently works normally on orbit. At the same time, Europe is developing the lightning imager (LI) on the third generation geostationary earth observation (MTG). LI is the first geostationary lightning observation satellite optical load of Europe, and the first lightning observation scientific load of Europe. Currently, FY4-01 of china can detect and identify lightning over china, with a remote sensing satellite lightning information system.

1.3 The innovation points

This paper proposes a remote sensing satellite lightning detection system with high detection rate and lower complexity, including sensor unit and electronics unit. Firstly, the system uses ultra-narrow band filtering technology and high frame rate detector to extract the spectrum of lightning signals. And at the same time, a continuous mean elimination method is adopted to identify the lightning signals. Finally, the adaptive double-threshold recognition method is utilized to detect the recognized lightning signals with an adaptive detection rate of no less than 95%. Compared with the existing lightning imager products, the system will have a simpler hardware system design, and more flexible and accurate detection recognition rate.

2. PRINCIPLE AND ANALVSIS OF LIGHTNING DETECTION

Lightning is an extended source when observed from space. Most of the channels formed in the lightning discharge process are several kilometers, and some are dozens of kilometers long, with an average diameter of 8 kilometers. A lightning bolt usually contains more than one return stroke, and some

lightning bolts contain only one return stroke. A complete lightning discharge usually lasts from a few hundred milliseconds to one second, and the time interval between two adjacent returns is usually tens of milliseconds. The average duration of each pulse is less than 1ms. The original spectral image of lightning taken by the non-slit spectrometer is shown in figure1.
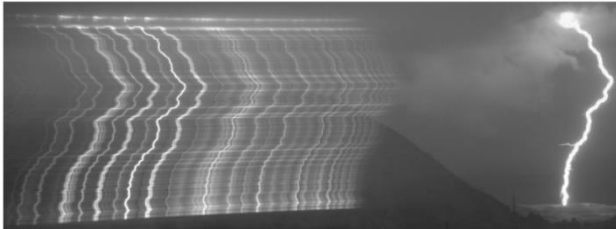

Figure1. The original spectral image obtained by a slit-free grating spectrometer

The researches show that the characteristics of lightning in the near infrared spectrum are more prominent than those in the visible spectrum and ultraviolet spectrum. The atomic lines in near infrared spectrum are the main radiation peak. And OI 777.4nm is one of the strongest spectral lines. The near infrared characteristic spectral lines of lightning are measured in a return stroke, which is shown in figure2, indicated that the near infrared spectral lines are mainly emitted by oxygen and nitrogen atoms. In general, the return current peaks within a few microseconds and then fades, since the total spectral intensity is positively correlated with the intensity of the discharge current. So in figure2, the total spectral intensity is gradually decreasing corresponding to the current attenuation after a return stroke reaches the peak.
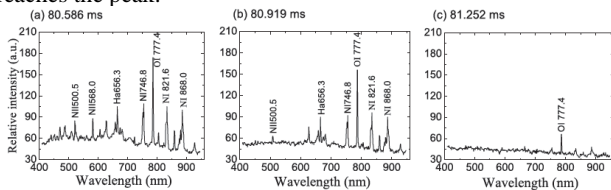

Figure2. A spectrogram of a return stroke

Figure3 shows the spectral diagram of a certain position of the discharge channel represented by the relative strength of the spectral line, where picture a and picture b are ground flashes, and picture c are cloud flashes. It displays that the structure and intensity of the infrared spectrum of lightning do not change much whether it is cloud flash or ground flash. It also shows the changes of the intensity of four spectral lines (777.4 nm, 820.0 nm, 844.7nm and 868.3 nm) in the near infrared bands of these three lightning flashes over time in figure 3, which come to the conclusion that the near infrared radiation in lightning has a long duration(about 120ms) and is relatively stable. Thus, this feature can be detected even when the cloud tops are illuminated by the sun. Therefore, the lightning detection system needs to detect optical pulses related to the emission line of neutral oxygen atoms in the lightning spectrum at 777.4nm.
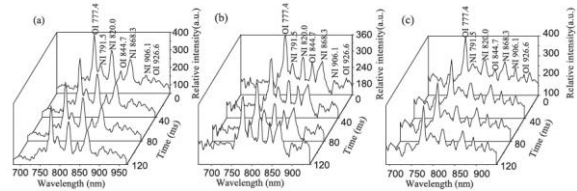

Figure3. The spectrogram of a discharge channel at a given position, represented by the relative strength of the spectral line

3. DESIGN AND IMPLEMENTATION OF AN LIGHTING DETECTION SYSTEM

3.1 System

The lightning detection system is mainly composed of sensor unit (including the refracting cylinder and the high frame rate CMOS camera), the electronics unit and the focal power supply unit, as shown in figure 4. The sensor unit completes the photoelectric conversion of incident signal and the conversion of analogy signal to digital signal. The algorithm of lightning detection and extraction, the measurement and temperature control of the camera and the secondary power distribution function are realized in the electronics unit. The focal power supply unit mainly provides power distribution for the focal components. The real-time event processing circuit is the key part of the electronics unit, which is used to realize the lightning detection algorithm. It receives the digital signal output from the focal component and then extracts the lightning signal from the slowly changing background. The realization of detection algorithm is competed by FPGA.
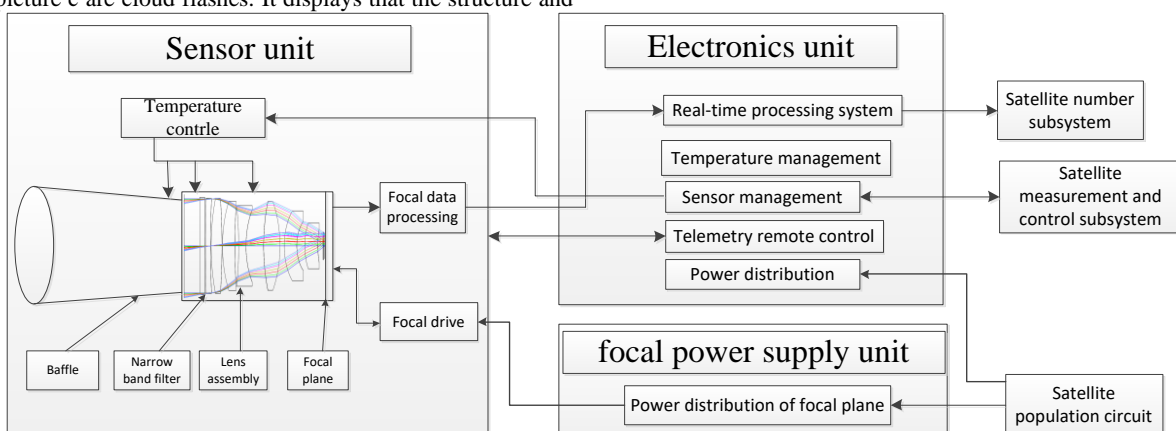

Figure4. System

3.2 Key Technologies

In order to maximize the efficiency of lightning detection, many important factors need to be considered in the design of detection system. These key technologies are summarized in the following section.

3.2.1 Sensor unit

The important consideration of the sensor unit are the ultra-narrow band filter and the high frame rate array CMOS.
(1) Ultra-narrow band filtering technology
The true test of a lightning-detection system is its ability to detect faint flashes of lightning from the illuminated cloud

top. Since the cloud is almost a lamer reflector when sunlight hits the cloud top, and its reflectivity is sometimes close to 1, there is a lot of unwanted sunlight around 777.4nm. Dark lightning events can be drowned out by random noise from background clouds simultaneously. So it is necessary to reduce the background signal by using the narrowest narrow-band filter that only allows the 777.4nm spectrum to pass through, because of the OI 777.4 nm is one of the strongest spectral lines of lightning as explained in section 2.

(2) High frame rate CMOS

The lightning detection system detects individual optical pulses caused by lightning on top of a bright cloud background illuminated by the sun. In order for these detected pulse signals to have better SNR, the frame rate must be optimized. The average duration of the lightning light pulse is shown in the figure 5.

The frame rate should be closely matched to the average duration of the pulse. If the frame rate is too low, then additional background with no valid signal will be detected, lowering the SNR. If the frame rate is too high, then the signal is split into multiple adjacent frames, reducing the SNR. The frame rate is 500 Hz, well matched to the duration of the lightning optical pulses.
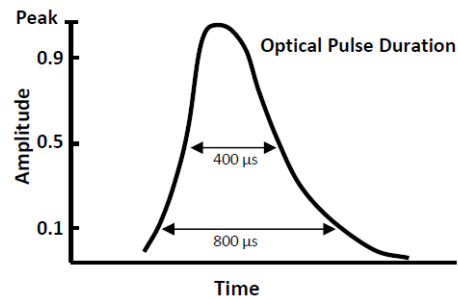
Figuer5. Typical lightning optical pulse profile

The frame rate and the CMOS FWC must also be matched. Lightning usually occurs in the afternoon, when the clouds are well illuminated by the Sun. And lightning generally forms in what appear to be thick clouds. The CMOS FWC must be large enough to accommodate the expected background of bright clouds. The lightning detection system uses a CMOS detector with a depth of about six million electrons that adapts to a bright background while leaving room to detect lightning events.

The frame rate, FWC and optical filter work together to optimize the signal-to noise ratio (SNR) of the detection.
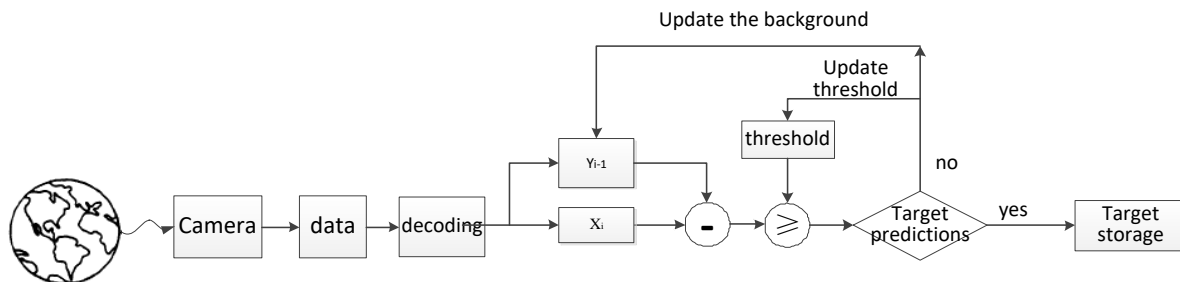
3.2.2 Electronics Unit

Figure6. Lightning detection algorithm

The electronics unit mainly carries on the lightning identification and extraction. Different from the "7 frame overlay algorithm" adopted by FY4 (01) satellite [2][9], this paper has proposed a continuous mean elimination (CME) method to detect the lightning event. The algorithm shown in figure 6 is realized on the real- time event processing circuit.

The lightning detection algorithm takes a "lightning event", which is a pixel of the corresponding detector, as the minimum detection unit. So it will detect any positive change of each pixel in each frame according to the threshold value already defined. Firstly, the estimated value of background in each pixel has to be calculated. The estimated value of background is calculated according to the following formula, where N is an adjustable time constant. X is current input signal. Y is the estimated value of background. (p,q) is the coordinate of the pixel. i means the number of the frame.

$$Y_i(p,q) = \frac{1}{N}X_i(p,q) + \frac{N-1}{N}Y_{i-1}(p,q) \qquad (1)$$

A lightning event is expressed as 72bit width, which includes: lightning location, lightning intensity, background value, threshold value.

The threshold is set according to the statistical mean of $\Delta d_i(p,q)$, and the formula of $\Delta d_i(p,q)$ is as follows:

$$\Delta d_i(p,q) = X_i(p,q) - Y_{i-1}(p,q) \qquad (2)$$

X is current input signal. Y is the estimated value of background. (p,q) is the coordinate of the pixel. i means the number of the frame.

If $\Delta d_i(p,q) > Threshold_i(p,q)$, then it is determined that there is a suspected lightning event in the current frame image data of the selected pixel; otherwise, it is considered that there is no lightning event in the current frame image data of the selected pixel.

In real-time event handlers, it is important to be able to select thresholds pixel by pixel. The following simulation further illustrates the need to control thresholds in each pixel. The left image of the figure 7 is a real on-orbit image, which shows that each pixel has a different brightness and shade in this small region. Where there are clouds, the pixels are brighter due to the reflection of the clouds on the sun, while where there are no clouds or shadows, the pixels are darker. The brightness of the pixel is different due to the different intensity of reflection. It is not difficult to conclude that the sunlit part of the cloud roof contains more total noise than the shaded part, and its signal-to-noise ratio is different, so a threshold cannot be uniformly defined.

The threshold lookup table method had to be adopted by FY4 (01) satellite and GLM to identify suspected lightning signal [1-2]. This method of traverse lookup table directly affects the response speed of the algorithm, and many storage spaces are need to open up to store threshold table at the same time. If the threshold table set is not appropriate, it must be adjusted on orbit, and the new threshold table is needed to be transmitted to the satellite from the ground. So the data upload function in hardware is necessary, which makes more complex to the operator using process. Therefore, the lightning detection system proposed in this paper adopts a new adaptive dual-threshold detection method, which determines the threshold $Threshold_i(p,q)$ according to the transient change value $\Delta d_i(p,q)$, and determines the suspected lightning signals that have been detected.

The threshold is set according to the statistical mean of $\Delta d_i(p,q)$, and the threshold can be adjusted adaptively in real time. At the same time, the threshold can be adjusted by satellite control command and control system according to the detection of ground data.

Detection rate and false alarm rate is originally a pair of contradictory body. The two can only balance, but can't have both. The system sets high and low double threshold detection. Whether to improve the detection rate or reduce false alarm rate can be selected through the double threshold adjustment. Choosing a high threshold for identification can reduce false alarm rate and identify the obvious point target signals accurately, but some point target signals with small energy value may be missed. Choosing a low threshold can improve the detection rate and identify the point target signal with a small energy value, but the false alarm rate will be higher.

The system adopts high threshold for background data below 100DN and low threshold for background data above 100DN, and can adjust the design value on orbit. This design method can avoid the need to upload the new threshold table frequently because of the unreasonable threshold setting in the ground test.

The system adopts the high-speed data transmission technology on orbit, which can receive the focal plane data by high-speed Serdes(>10Gbps), and uses Xilinx V7-fpga to realize the data processing. By comparison, GLM use space wire protocol developed by ASIC technology to transmit data and telemetry signal at the same time. Its development time is too long, with highly cost, and it is not easy to change.

Through the above design method, the system can reduce the volume, power consumption, weight of the system greatly. The system weight is only 90kg. It's 8 times as massive as FY4(01), and it weighs less than 30 kg more. The power consumption can be down to 190w, which is much lower than FY4(01).

4. EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Simulation results of the algorithm

This algorithm is simulated to verify the detection result, according to the on-orbit data of FY4-01 satellite. Compared with the detection result of the real time algorithm on orbit and the following conclusions are obtained.

Figure 7 shows the simulation results, compared with the on-orbit data. The left image is the on-orbit data, while the right image data is the highlighted lightning signal after processing. The relationship between lightning signal and background value are shown in figure 8 in a three-dimensional mode, which indicate intuitive that the lightning signal can be extracted through background filtering if there is a lightning signal in the image signal collected after spectral extraction.
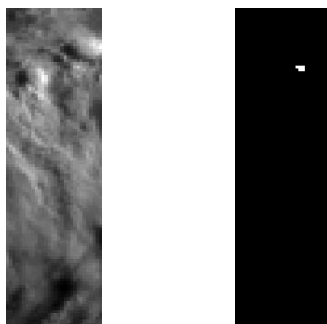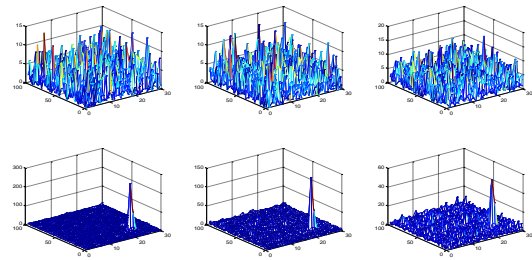

Figure7. Image frame compere

Figure8. 3D view of lightning signals

Figure 9 has shown the energy spectrum or DN value of some pixel point during the night. Figure 10 has shown the energy spectrum or DN value of some pixel point during the daytime. The data length is 24800 frames, about 1min, which was got from the on-orbit data. The red points in figures are the detected signals.
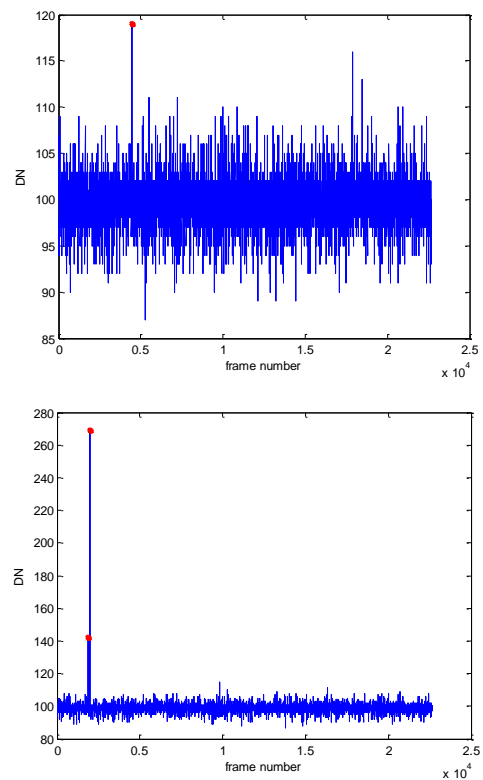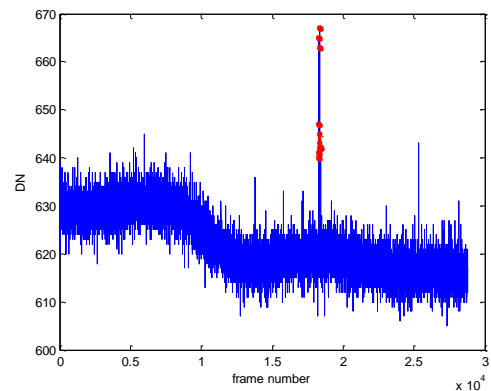

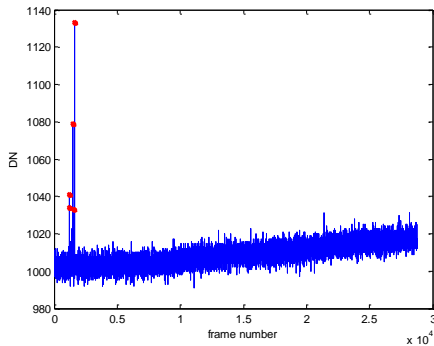Figure9. energy spectrum of night lightning

Figure10. Energy spectrum of daytime lightning

Several conclusions can be drawn from these two pictures. Firstly, the duration of simulation data in the figure is almost 1 minute. However, for a certain pixel, its energy spectrum shows a trend of slow change. Therefore, for the sudden change of lightning signal, continuous mean elimination (CME) method can be used to accurately detect it. Accordingly, the system can be used to detect other point or surface target by the slow change of the background according to the different characteristics of the detection target, such as the large-scale fire disaster or military target.

Secondly, the images taken during the day are the cloud top images under sunlight, while the imaged taken at night are not exposed to sunlight, so their noise is the same as the electronic noise of the instrument, but different from the optical or radiated noise. It is obvious from the figure that the daytime pixel has more total noise than the night image pixel or the shadow image pixel. Therefore, weak lightning signal during the day will be more difficult to detect.

The system can get more accurate background estimation by CME method, and the detection rate of weak signal can be improved by using lower threshold.

4.2 System verification

The physical verification of the lightning detection system is carried out according to the system verification scheme shown in figure11. The verification test connection diagram is shown as follows.
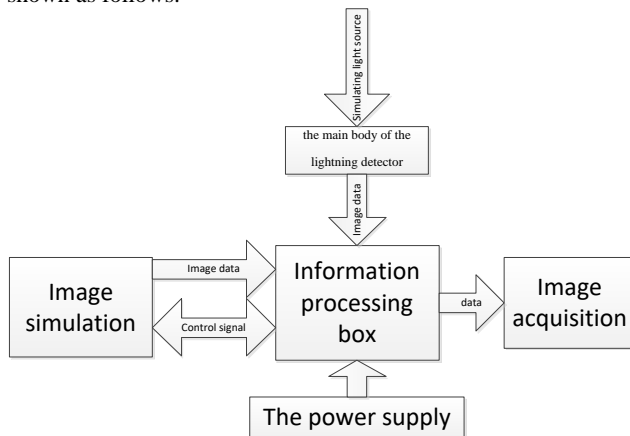

Figure11. System test connection

According to the figure above, the image simulation is used to simulate the signal source of the focal to output the image. There are some on-obit data stored, which can be send to the information processing box. Signals on certain locations will be superimposed on it. After the real-time processing of the electronics unit, the results are displayed to the image acquisition device synchronously to verify the real-time processing results of the electronics unit. The simulated image

or the on-orbit data of 01 satellite can both be selected to send. The collected lightning events, could be stored in the local area to verify the correctness of the result. And the second method is to verify the whole system with real shooting. The detected results are shown in figure 12. The white lines show in figure12 are lightning events detected by this system.

The image simulation will be substituted by the sensor unit finally. The image acquisition can also get the detected result. But it is difficult to calculate the accuracy of detection result.
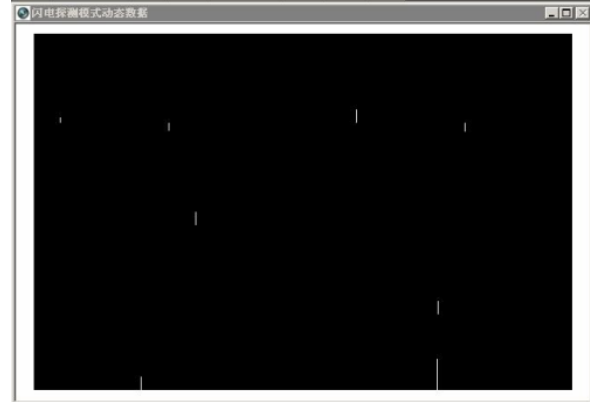

Figure12. The result of ground image acquisition system

The detection rate of the lightning detection system can be obtained by dividing the number of lightning events correctly by the number of all lightning events in the sample. The detection rate of this system is 60%~95%. It is difficult to detect the weak lightning signal in daytime because of the influence of the noise of shrapnel. The detection rate can be improved by using lower threshold value.

Figure13. Experimental environment

Figure13 has shown the experimental environment of this system. The right was the image simulation, and the left was the image acquisition. The picture on the screen was the detection result.

5. INERNATIONAL

The technical indicators of the lightning detection system and similar foreign instruments are shown in table1 [3].

The scheme proposed in this paper is superior to other international products in detection rate, system quality and power consumption, achieving high detection rate and low complexity while achieving full disk lightning detection.

Table 1

Index	OTD	LIS（TRMM）	GLM（GOES-R）	LI（MTG）	FY4	This system
Focal image number	128*128		1372*1300	570*570*4	400*300*2	1400*1400
Ground coverage (km^2)	1300*1300	520*520	Full disk	Full disk	3200*4800	Full disk
Probe spectral channels	777.4nm	777.4nm	777.4nm	777.4nm	777.4nm	777.4nm
Band width	-	1nm	1nm	1nm	1nm	1nm
Frame time	2ms	2ms	2ms	2ms	2ms	2ms
Detection rate	25%	about90%	70%~90%	60%~90%	theory90%	60%~95%
weight	18kg	20kg	114kg	101.6kg	64kg	90kg
Power consumption	-	30W	290W	194W	230W	190W
Positioning accuracy	-	1pixel	1 pixel	1 pixel	1 pixel	1 pixel

6. CONCLUSION

This article first briefly describes why lightning detection is needed. In the second part, the spectral characteristics of lightning had been analysed simply. Then a design method of remote sensing lightning detection system with high detection rate and low complexity is presented in the third part. In addition, the ultra-narrow band filtering technology and high frame rate detection in the optical part, as well as the continuous mean elimination (CME) method and adaptive threshold detection method designed in the electronics part are described in detail. The effectiveness of the algorithm is verified by simulation, and the detection result of the whole system is verified by the demonstration validation system. At the end of the paper, the key technical indexes of the lightning imaging system and similar instruments in the world are compared, which are better than the existing ones.

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