

SOPC-based VLF/LF Three-dimensional Lightning Positioning System

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Abstract — Lightning monitor technology is developing on the orientation of high accuracy, multi-lightning detect, three-dimensional monitor and lightning positioning. An SOPC-based VLF/LF three-dimensional lightning positioning system is presented in this paper. On the Altera's Cyclone II platform, a Nios II embedded CPU is constructed. Through the AVALON bus, hardware modules, such as the controller of the signal collection board, the AD's controller, the processor of lightning signal, the synchrotimer, the smoothing filter, the Zigbee controller, the network interface and the memory management IP, communicate with the CPU. This hardware-software collaboration structure efficiently decreases the complexity of the design and improves the system's flexibility. Based on the lightning detecting instrument, a three-dimension lightning positioning network is setup. Through the multi-station time difference of arrival (TDOA) algorithm, the network can detect a thunderstorm's generation, progress and attenuation, which is important for both the research and the early forecasting of the thunder.

Keywords — lightning, three-dimensional positioning, time difference of arrival, field programmable gate array, thunderstorm

I. INTRODUCTION

As a strong discharge phenomenon, lightning is an air breakdown, caused by electric charge accumulation of the relative movement of the ice crystal or moisture in cloud. Lightning could kindle a forest, destroy a building, or even hurt a human, which makes a severe influence on the civil and military aircraft of aerospace, communication equipments and electric apparatus. So the research of lightning monitoring and prevention is highly concerned in most countries.

Besides the direct cloud-to-ground (CG) lightning, the intracloud (IC) lightning attracts researchers' attention in these years. Generally speaking, IC lightning is the precursor of the disastrous weathers, such as the thunderstorm, heavy rain. It is the most frequent lightning event, and the first discharge of CG lightning normally also follows IC flashes. So the ultimate aim of lightning detect is the three-dimensional monitoring of both CG flash and IC flash [1]. When it is achieved, the lightning's parameters, such as the three-dimensional position of a lightning, the relationship between the height and frequency of IC lightning, the ratio of the positive lightning to the negative lightning, and the duration of the thunderstorm, can be calculated. Go a step further, the progress of a thunderstorm can be observed, and a trend of thunderstorm on the three-dimensional area can be predicted. It is available

on the monitor of the strong convection disastrous weather, the development of the weather forecast, and the thunder and lightning disasters defense.

Many countries and regions, like America, Europe, Japan, Brazil and Australia, have setup lightning monitor network. From 1984 to 1989, America constructed three separate lightning detect local area network, which based on magnetic direction lightning detect instrument. In 1989, America setup its national lightning detect network (NLDN) [2]. In 1995, NLDN was updated by equipping the VLF/LF time difference direction-finding hybrid detector (IMPACT location method) station [3,4], which realized the detection of CG lightning and the relative return stroke [5]. Nowadays, the lightning detect efficiency of NLDN has over 95%, and the average precision of positioning is 250m. Besides that and in 2011, America prepares to upgrade the NLDN to a three-dimensional lightning detect net by combining the VHF interference measure method and the VLF/LF IMPACT technology. In 2007, the atmospheric research group in the University of Munich developed the Europe lightning detect network (LINET) [6], which was composed of 90 sensor stations, and located in the 17 countries of Europe, such as Germany, France, Belgium, Finland, Poland, Italy, Britain, Spain and so on. Its detect region covers the whole Europe. Besides the detection of CG lightning and IC lightning, it can support the three-dimensional positioning, whose precision achieves 150m.

The study of the lightning monitor in China started at 1960's. At 1970's the direct-finding detection system was developed. At the end of 1980's, the ALDF system was imported from the LLP Company. In 1997, the National Space Science Center of the Chinese Academy of Sciences developed the IMPACT system. By employing it, China Meteorological Administration started the national lightning detect network

in 2004, and finished it in 2007. Nowadays, the net has 311 detect stations, which cover the 80% region of China. Comparing with the three-dimensional detect nets of America and Europe, that net can only detect CG lightning and give the two-dimensional positioning, lacking of the ability of IC lightning detect and regional thunder forecast. It must be upgraded!

On the support of the National Science & Technology Pillar Program for the 11th five-year plan of China, the Meteorological Observation Centre of the China Meteorological Administration, the School of Physics and Technology of Wuhan University, and the National Space Science Center of the Chinese Academy of Sciences collaborated to develop a high precision three-dimensional CG&IC lightning positioning system in 2008. Employ FPGA as a controller, the new system's performance and stability are improved. Because of its compact structure, the power consumption is also decreased. Through the test in 2010 and in 2011, the new system is verified. In 2012, the VLF/LF three-dimensional lightning positioning service network of Jiangsu Province has been applied. In that network, 16 VLF/LF lightning detecting instruments setup on 16 meteorological stations, and a lightning data center takes the charge of data process.

II. THREE-DIMENSIONAL POSITIONING ALGORITHM

Time difference of arrival (TDOA) technology [7,8] derives from the "Roland" navigation positioning system, which determined its own position by the signals from three known-position transmitters. But different from it, a TDOA system in lightning detection uses three known-position receivers to determine an unknown-position transmitter.

Through the dealing the data of radiation arrival time from three or more than three observation

stations, TDOA algorithm localizes the radiator's position by hyperbolic curves. The time difference of the radiation arriving two stations can setup a hyperbolic curve, in which the two stations are on the focuses. Adding the third observation station, two hyperbolic curves can be confirmed, and their intersection determines the radiator' position in a two-dimension plane. By that analogy, three hyperboloids can be got if we have four or more than four stations. Using the intersection point of the intersection lines of these hyperboloids, the position of a radiator can be determined.

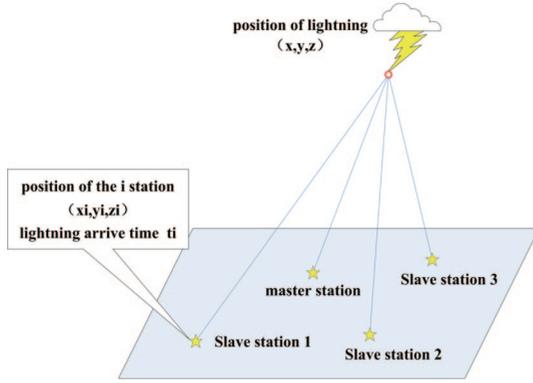


Figure 1. Schematic of a four-station TDOA positioning

As Figure 1 shows, the position of the observation stations are (x_i, y_i, z_i) , in which $i=0$ stands for the master station, and $i=1,2,3$ stand for the slave stations. The position of the lightning is set as (x, y, z) . The distance between it and the master station is R_0 , and the distances between it and the slave stations are R_i . The difference between R_0 and R_i is ΔR_i . So TDOA algorithm can be described as,

$$\begin{cases} R_0^2 = (x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 \\ R_i^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 \quad i = 1, 2, 3 \\ \Delta R_i = R_i - R_0 = c(t_i - t_0) \end{cases} \quad (1)$$

Submitting the last two equations into the first equation, one can get,

$$(x_0 - x_i)x + (y_0 - y_i)y + (z_0 - z_i)z = k_i + R_0 * \Delta R_i \quad (2)$$

where

$$k_i = \frac{1}{2} [\Delta R_i^2 + (x_0^2 + y_0^2 + z_0^2) - (x_i^2 + y_i^2 + z_i^2)] \quad (i = 1, 2, 3)$$

Eq.2 can be rewrite as the following matrix,

$$\begin{bmatrix} x_0 - x_1 & y_0 - y_1 & z_0 - z_1 \\ x_0 - x_2 & y_0 - y_2 & z_0 - z_2 \\ x_0 - x_3 & y_0 - y_3 & z_0 - z_3 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} k_1 + R_0 * \Delta R_1 \\ k_2 + R_0 * \Delta R_2 \\ k_3 + R_0 * \Delta R_3 \end{bmatrix} \quad (3)$$

Eq.3 is a linear equation set about (x, y, z) with parameter R_0 , so we can represent (x, y, z) as R_0 's function. Submitting it into Eq.1, R_0 can be solved. Then, (x, y, z) can be calculated.

For the case of no solution, we determine a quasi optimum solution for the positioning. It is the point that has the minimum distance sum to the three hyperboloids, determined by the four observation stations. Set that point as T (x, y, z) , and its distances to the three hyperboloids are $d_1(x, y, z)$, $d_2(x, y, z)$, $d_3(x, y, z)$, the distance sum is,

$$F(x, y, z) = d_1^2(x, y, z) + d_2^2(x, y, z) + d_3^2(x, y, z) \quad (4)$$

Let the partial differentials of Eq.(4) equal zero, we have,

$$\begin{cases} \frac{\partial F(x, y, z)}{\partial x} = 0 \\ \frac{\partial F(x, y, z)}{\partial y} = 0 \\ \frac{\partial F(x, y, z)}{\partial z} = 0 \end{cases} \quad (5)$$

Form Eq.5, the quasi optimum point T can be calculated.

III. SYSTEM ARCHITECTURE

A. General Framework

Our three-dimensional lightning positioning network absorbs the advantages of the IMPACT-ESC and the LINET. The arrival time of lightning’s VLF/LF electromagnetic pulse is accurately measured by using the GPS time calibration. Based on TDOA algorithm and the wideband net communication technology, the lightning’s parameters, such as the generation time, the intensity and the three-dimensional coordinate are calculated. Then the three-dimensional positioning is realized.

The lightning positioning network is composed by more than four lightning detecting instruments (setup on four meteorological stations, and the distance between each two stations is more than 70km) and a lightning data center. The lightning detecting instrument takes the charge of collecting the lightning signal and transports signal to the data center. The lightning data center calculates lightning’s three-dimensional position based on the data from the lightning detecting instruments,

and transports the result to a 3D graphic interface in the form of an UDP package. More than that, the lightning data center saves all lightning data on an Oracle data base, and then the data is used in relative applications. This Framework is shown in Figure 2.

B. Specifications

According to the lightning’s characteristics and the requirement of the three-dimensional positioning, the following specifications are pointed out.

[1]. The specifications of the network:

- Lightning type:
 - positive cloud-to-ground flash (+CG)
 - negative cloud-to-ground flash (-CG)
 - positive intracloud flash (+IC)
 - negative intracloud flash (-IC)
- Three-dimensional positioning accuracy:
 - The horizontal error is less than 300m (on the region of the stations).
 - The vertical error is less than 500m (on the region of the stations).

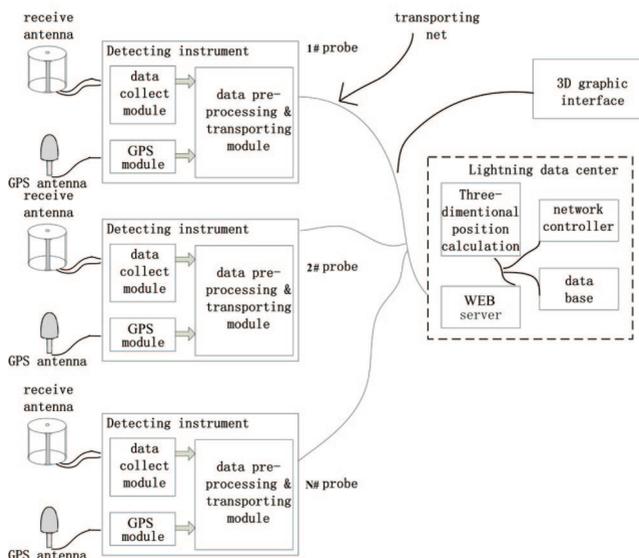


Figure 2. General framework of the three-dimensional lightning positioning network

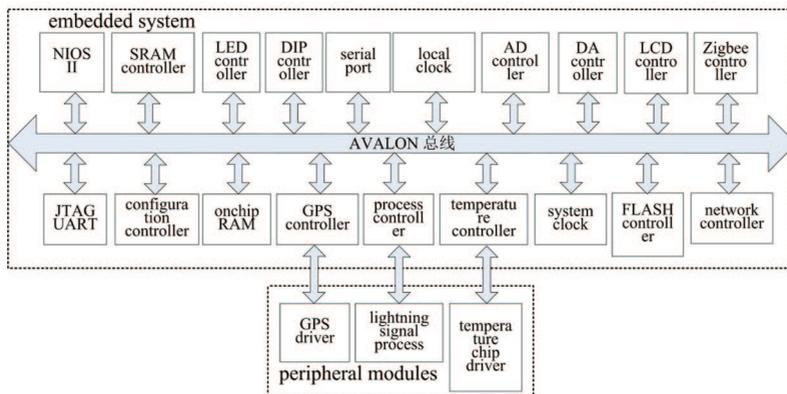


Figure 4. Structure of the SOPC system

module [11] and two wired ports (RS232 & RJ45) are configured for communication. The schematic of the lightning detecting instrument is shown as Figure 3.

FPGA is the key device of the lightning detecting instrument. In a Cyclone II EP2C series chip, the function modules, which are mentioned above, are connected by an AVOLON bus and controlled by NIOS II [12], an embedded CPU. The structure of this SOPC system is drawn in Figure 4.

The embedded software of the SOPC system completes the functions of system operation, such as the system initiation, self checking, interrupt routine, lightning signal judge, GPS time service, local clock management, state management, and communication with the upper computer. The software's flow chart is drawn as Figure 5.

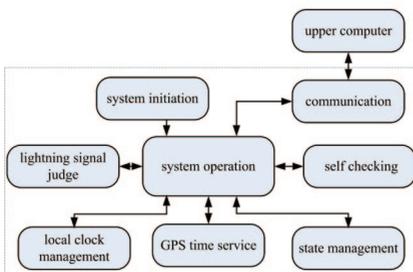


Figure 5. Flow chart of the embedded software

The system initiation function realizes the initial state setup for the whole SOPC system, including the interrupt set, the ADC initiation, the RAM checking, the GPS detecting, the local clock calibration, and so on. The self checking function checks the system's status and calculates the temperature and time compensation [13]. The system operation is the main module, which realizes the analysis of the lightning data and the control of the embedded system.

IV. TESTS AND APPLICATION

A. Consistency Test of the Lightning Detecting Instrument

To verify the lightning detecting instrument's consistency character on the flash receiving time and the flash pluses amplitude, comparison experiment had been done at the Beijing Meteorological Station in 2010. Five lightning detecting instruments were tested by the same lightning signals from the 10 pm. 2010-08-08 to the 10 am. 2010-08-09. During that time, 6083 lightning are monitored. The results of a twice stroke lightning on the experiment are shown as Table I and Table II.

TABLE I. TEST RESULT OF THE FIRST RETURN STROKE

No.	Time*	Angle	Magnetic field intensity	Electric field intensity	Leading edge of lightning	Trailing edge of lightning
0	1.454	193.94	0.46	0.27	26	202
1	1.455	189.70	0.48	0.29	28	205
2	1.455	192.86	0.47	0.29	26	204
3	1.454	188.54	0.44	0.29	26	202
4	1.455	193.79	0.47	0.27	29	209

* Only mS is shown, since the other part of the measured time of the five instruments are the same as 2010-08-09 01:37:57.284.

TABLE II. TEST RESULT OF THE SECOND RETURN STROKE

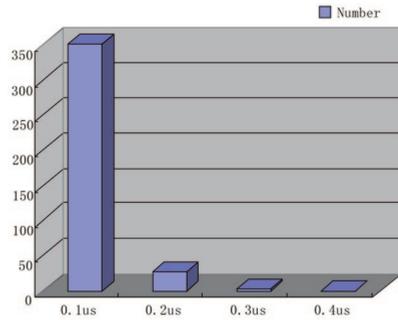
No.	Time*	Angle	Magnetic field intensity	Electric field intensity	Leading edge of lightning	Trailing edge of lightning
0	1.790	194.01	0.45	0.29	21	240
1	1.789	189.21	0.45	0.35	22	245
2	1.789	192.41	0.44	0.52	20	245
3	1.789	187.97	0.40	0.52	21	241
4	1.789	193.96	0.44	0.55	23	259

* Only mS is shown, since the other part of the measured time of the five instruments are the same as 2010-08-09 01:37:57.375.

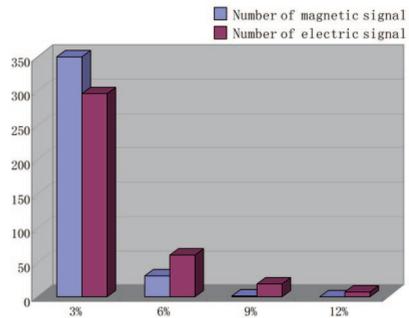
From the above tables one can see, the five lightning detecting instruments have a good consistency for a single lightning. To show the instrument's consistency statistically, 380 data are chosen randomly from the 6083 lightning, and the statistical results of the consistency are drawn in Figure 6.

As Figure 6 shown, on the flash receiving time measure, the 92% data's error is less than 0.1 μ S, and the 99% data's error is less than 0.2 μ S. On the magnetic field intensity measure, 92% data's error is less 3%, and the 98% data's error is less than 6%. On the flash pluses of electric field intensity measure, 78% data's error is less 3%, and the 92% data's error is less than 6%. The accuracy of the lightning detecting instrument fulfills the specification. Perhaps the relative low accuracy of the electric field intensity measure is caused as follows. The first reason is that the electric field signal is easy to be disturbed by the background noise. The second one is that the waveform of electric field signal is different with the magnetic field signal, which brings bigger error in waveform judge. The last one is that since the five instruments are lined on the test, the minor

differences of the electromagnetic environment between them also bring error.



(a) consistency of arrival time



(b) consistency of magnetic signal and electric signal

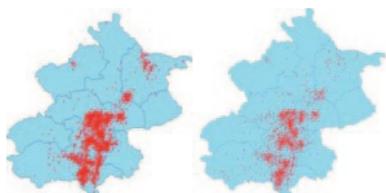
Figure 6. Statistic result of consistency experiment

B. Test of the Network

A test network of the three-dimensional lightning positioning system was setup on July, 2011. The master station was set on the Beijing Meteorological Station in the southern suburb, and five slave stations were set on Fengning, Zhangjiakou, Zunhua, Tianjing and Baoding. The distance between the master station and each slave station is about 150km, which is suitable for a high accuracy.

By the test network, about 200,000 lightning happened have been detected. Through the analysis of these lightning, we find that the highest lightning detect efficiency of the network is near

the master station (station in Beijing). Using the data on 2011-08-26, we verify our test network's efficiency by set the data of China's National Lightning Monitoring Network (CNLMN, A two-dimensional net we mentioned in section I, which is completed in 2007 and it can not detect IC lightning) as a standard. The test network monitored 3202 lightning, while CNLMN monitored only 1921 lightning. The comparison is shown in Figure 7.



(a) data from the test net (b) data from CNLMN
 Figure 7. Lightning distribution comparison between the test net and the national net

It shows the lightning distribution regions of the two nets are similar. We believe the extra lightning of the test net is IC lightning, which can not be detected by CNLMN.

To confirm that conclusion, the further analysis is given. Figure 8 illustrates IC flash (the yellow point) and CG flash (the red point) from the data of the test net. In it, there many yellow points upon the red points. It implies the lightning number of the test net (the sum of the yellow points and the red points) shall bigger than the lightning number of CNLMN (the number of the red points), which is compatible with Figure 7.

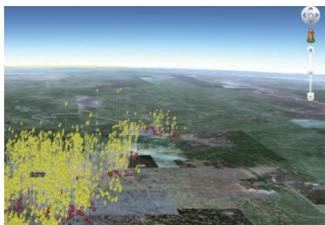


Figure 8. Three-dimensional distribution of the lightning from the test net

As we known, IC flash happens in midair and CG flash happens near the ground. Figure 9 gives a further quantitative research. It shows the height distribution of the lightning. From the statistic, the ratio of the IC lightning and the CG lightning can be known.

From the above analysis, we can affirm that the new three-dimensional lightning positioning network has a good consistency with CNLMN. Besides detect CG flash, it can position IC flash and give the three-dimensional distribution of lightning in a thunder [14], which is a significant improvement for both the lightning study and the thunderstorm forecast.

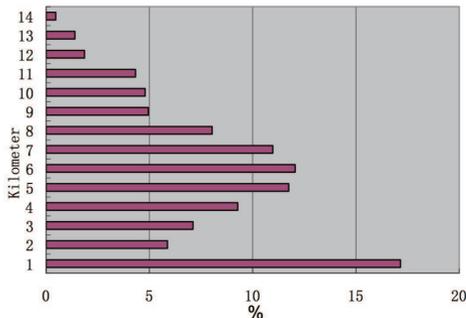


Figure 9. Height distribution of the lightning data from the test net

Besides that, the comparison of the lightning data and the radar echo map also supports our conclusion. The area distribution of the lightning is compatible with the cloud distribution form the radar echo map.

C. Application in thunderstorm forecast

Since the test net's performance has been certificated, a service network is setup on July, 2012. It has 16 lightning detecting instruments in Jiangsu Province. This service net monitored 177940 lightning from 2012-08-15 to 2012-09-15. There were 133598 CG flash and 44342 IC flash, the ratio of IC flash was 24.92%.

Figure 10 gives the lightning data on the south region of the Jiangsu Province. There was a strong thunderstorm in that area at the dusk of 2012-09-08. Follow the above analytical method, we see the data of the national net as CG flash and the data of the service net as the sum of CG flash and IC flash. From it one can see, at the beginning of the thunderstorm, the ratio of IC flash in all lightning is high. With the progress of the storm, the ratio gradually decreased. This trend is compatible with the theory that IC flash happens before CG flash and the decrease of the ratio of IC flash means the enhancement of a thunder [15]. Since IC flash has little influence on people but CG lightning has a heavy effect on our life, so through IC flash monitor by this new three-dimensional lightning positioning system, the disastrous thunders can be forecasted.

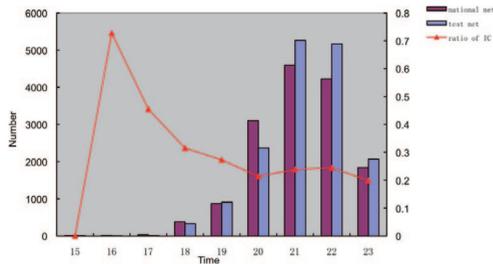
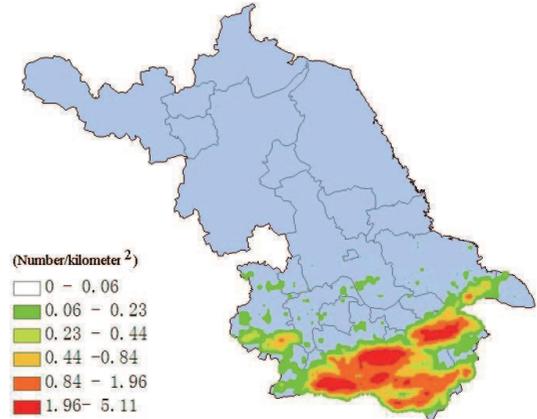


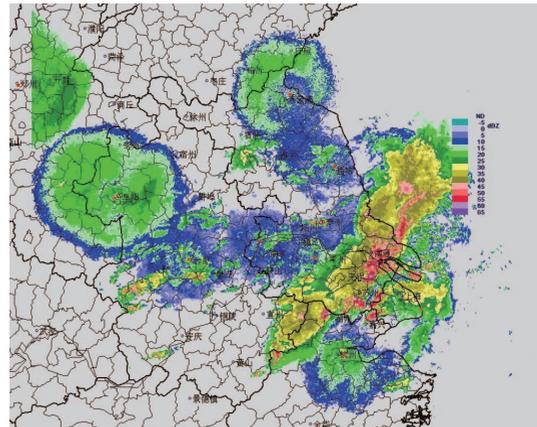
Figure 10. Lightning record of the south Jiangsu Province at 8th Sept. 2012

The comparison of the lightning and the radar echo map in this case also had been done. The area distribution of lightning in Figure 11(a) is compatible with the cloud distribution by the radar echo in Figure 11(b). The lightning happened on the region, in which the radar echo is over 35dBz. For the region that the radar echo is higher than 45dBz, the lightning was intensive. More important, the data of Figure 11 was at the 15:00 pm, 2012-09-08, which is just at the start of the thunderstorm in Figure 10. That supports the three-dimensional lightning positioning system can be used on thunderstorm forecast from another

perspective.



(a) lightning distribution map



(b) basic radar reflectivity map of 1.5°

Figure 11. Comparison of the lightning data and the radar echo map

CONCLUSIONS

In this paper, an SOPC-based VLF/LF three-dimensional lightning positioning system is introduced. The system is composed of three-dimensional lightning detecting instruments, a lightning data center and the relative application services. This system ends the history that Chinese lightning detecting cannot monitor the intracloud lightning and cannot measure the three-

dimensional position of a lightning.

As the key of the whole system, the three-dimensional lightning detecting instrument is SOPC-based and is implemented on an Altera's Cyclone II FPGA. By the virtue of this platform, the process speed of lightning analysis is increased, the size and the power consumption are decreased. As a result, the stabilization and the reliability of the instrument are improved. Through a series tests, this instrument achieves the international standards.

Besides the above work, we are managing to promote the lightning positioning system in near future. To further improve the positioning accuracy, we are studying a novel positioning technology based on direct 3D least square method. Since the radius of the earth changes with the latitude and the transmission of electromagnetic wave is influent by the surface, the earth's ellipsoid model and the calibration of electromagnetic wave transmission is going to be researched.

The three-dimensional positioning of lightning can be used to analyse the lightning phenomenon. Moreover, combining with the other factors of the weather forecast, the three-dimensional lightning positioning system can monitor the generation, the progress, and the attenuation of a thunderstorm, which is important for both the scientific research and the forecast of the strong convention weather.

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