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# EVALUATION OF THE NEW LS7001 NETWORK IN THE CHUBU REGION OF JAPAN

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## 1. INTRODUCTION

Lightning Location Systems (LLS) detect the electromagnetic field signal caused by a lightning discharge with two or more sensors and estimate the lightning position and the peak current value. They are widely used all over the world (Cummins, 1998). In Japan, electric power companies began installing LLS networks more than 20 years ago. They have been using the real time lightning location data from those systems for a long time to make their electric power company equipment maintenance work more cost efficient (Suda, 1998) (Suzuki, 2006).

Until recently, Chubu Electric Power Company operated an LLS consisting of eight IMPACT sensors in the Chubu region of Japan. In order to utilize the LLS more effectively and to expand the range of lightning observation, Chubu Electric Power upgraded the eight IMPACT sensors to ten LS7001 sensors over a two year period in cooperation with Sankosha.

As a result of that effort, the performance of the LLS in the Chubu region has been enhanced and the improvement in lightning detection efficiency was especially remarkable. We will describe the new upgraded LLS in this paper and present the results of our preliminary evaluation of lightning data collected by the network.

## 2. SYSTEM OUTLINE

### 2.1 UTILIZATION OF LLS DATA

Chubu Electric Power is one of the ten electric power companies in Japan and provides electric power to Aichi Prefecture, Mie Prefecture, Gifu Prefecture, Nagano Prefecture, and a portion of Shizuoka Prefecture (See Figure 1). In this region, lightning occurs frequently and the Isokeraunic Level (IKL; annual thunderstorm days) is over 35 in some areas of Gifu Prefecture making it one of the most lightning prone areas in Japan. The LLS network was expanded to provide better coverage near the Japan Sea coast where transmission lines have been built. Winter Lightning, a phenomenon unique to this area of the world, occurs here and the IKL in this area also exceeds 35 days.

The LLS can output the position of each lightning stroke, the polarity of the electric discharge and an estimate of the peak current in real time. Chubu Electric Power makes good use of that lighting data. The company is able to inspect transmission lines more efficiently when lightning caused breakdowns occur. An emergency maintenance team is put into action when lightning is detected and a lightning data service has been established to provide information to the customer. Chubu Electric Power also compiles lightning statistical data which is used in deciding when transmission line maintenance checks are required and in the design of suitable power line lightning protection systems. LLS data contributes to a reduction in maintenance work expenses.

Chubu Electric Power has been constantly evaluating their original network performance during LLS operations (Shimizu, 2000).

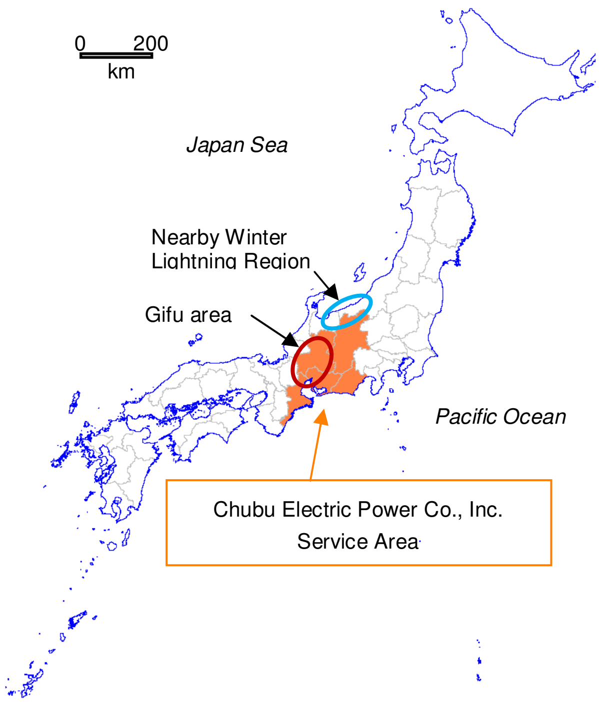



Figure 1: Japan and the Chubu Electric Power service area

## 2.2 THE EVOLUTION OF THE CHUBU LLS

At first, Chubu Electric Power introduced the LLS as a research system to verify the usefulness of its the lightning location capability. Then, after the lightning location capability of the LLS had been confirmed, the system was placed into service as a company approved observation system. The lightning observation range of each generation LLS is shown in Figure 2. It shows how the range of observation has been extended. A brief description of each generation LLS is below.

### (1) ALDF Network (The 1st Generation)

The LLS for research was constructed in 1986 to verify the accuracy of its lightning location capability. It consisted of four ALDF sensors (Nakatsugawa, Ogaki, Atsumi, and Ueno) and a PA80-02 Central Processing Unit. The ALDF sensor uses MDF (Magnetic field Direction Finding) technology to locate lightning. The sensors were set to medium gain (gain 2) and installed at baseline intervals of around 100km. In 1991, two more ALDF sensors were added at Shimada and Takayama.

### (2) IMPACT Network (The 2nd Generation)

The LLS that became the company approved observation system was constructed in 1998. It consisted of six IMPACT-ES sensors (including the two additional sensors at Takayama, and Shimada) and an LP2000 Central Processing Unit. The IMPACT-ESP sensor uses both TOA (Time Of Arrival) and MDF technology for lightning location. That results in more accurate lightning positions. Two more IMPACT-ESP sensors were added in 2001 at Fuji and Nagano, and the lightning observation range was extended to cover the northeast area. At that point, almost the entire Chubu Electric Power Company supply region was covered by the LLS. A CP7000 Central Processing Unit was installed in 2006 to improve lightning data processing.

### (3) LS7001 Network (The 3rd Generation)

A new power plant and a new transmission line were to be built outside the Chubu Electric Power service area and it was decided that a new LLS would be installed in 2010 and 2011. It consisted of a total of ten LS7001 sensors including two additional sensors at Noto and Niigata. Thereby, the range of lightning observations was extended to the coastal area of the Sea of Japan. Although the LS7001 sensor uses MDF and TOA technology like the IMPACT-ESP sensor, improvements in the processing speed and detection efficiency were achieved through the digitization of signal processing. The sensors were installed at baseline intervals of 80km to 150km as shown in Figure 3 in order to maximize range while maintaining location accuracy at 0.5km or better. Although the baseline intervals of the sensors were 100km or more, the sensors were set continuously at medium gain. The central processing unit and the sensors are connected through a network circuit. An LS7001 sensor installation example is shown in Figure 4.

The configuration of the network of sensors in the 3rd generation LLS was determined in an effort to optimize the lightning observation area. The site selection process is described below.

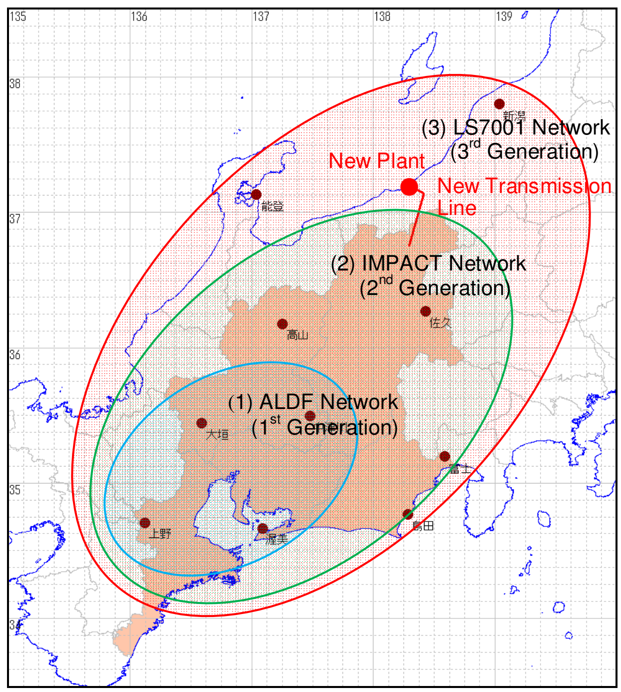
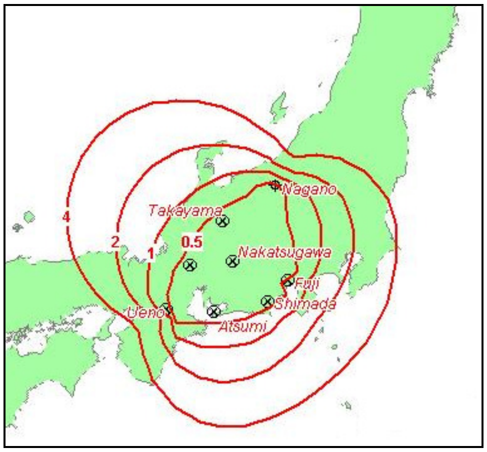



Figure 2: The growth in lightning observation range by Chubu LLS generation and the current LS7001 network sensor positions



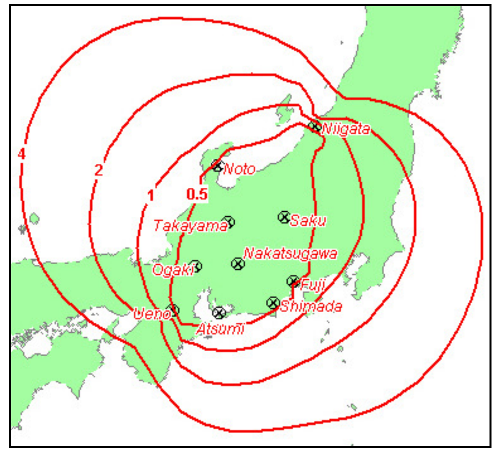




Figure 3: Location accuracy projections for the 2nd generation (IMPACT, left) and 3rd generation (LS7001, right) showing location accuracy range contours of 0 to 0.5 km, 0.5 to 1 km, 1 to 2 km, 2 to 4 km, and 4km or more)

Figure 4: LS7001 sensor installation example

### 2.3 DETERMINING THE LS7001 SENSOR NETWORK CONFIGURATION

A new power plant and a new transmission line to be built on the coast of the Sea of Japan were to be outside the Chubu Electric Power Company service area and there was concern that the existing IMPACT Sensor LLS would not be able to detect and locate lightning with sufficient accuracy in that region. The following procedures were used to determine the best number and optimal configuration of sensors for the new LS7001 network so that it would be able to accurately locate lightning in the nearby winter lightning region.

**(1) Verification of the location accuracy of the existing LLS (IMPACT network)**

The location accuracy of the existing LLS has been confirmed based on the location of power transmission towers where lightning caused transmission line faults had actually occurred. GPS timing in the LLS lightning location data provides micro second order timing accuracy. However, the power line fault data timing accuracy is on the order of several seconds to sometimes several tens of seconds. Therefore, when the LLS and line fault time differences were less than one minute, we assumed that they were the same event. When two or more lightning location data were found in the same one minute line fault time window, the lightning location data nearest to the power line fault position was selected. However, events reported by the LLS in the same time window but located 25km or more away from the power line fault location were excluded. In this analysis, 620 power line faults detected in the Chubu Electric Power area from April 2005 to September 2008 were used. Our analysis of that data set showed that the detection efficiency of the existing IMPACT LLS was 98.1% and its location accuracy was 1.1km (See Table 1).

Table 1: IMPACT LLS location error and detection efficiency when compared to power line fault data in the Chubu Electric Power area

| Number of lightning faults | Number concurrent with lightning location data | Detection efficiency | Location error (Average) |
|---|---|---|---|
| 620 | 608 | 98.1% | 1.1km |

To verify the accuracy of the IMPACT LLS in the nearby winter lightning region, we used the data from 132 power line faults in the period from April 2005 to September 2008 and analyzed that data set in the same way. The detection efficiency was 97.0% and location accuracy was 2.7km (See Table 2).

Table 2: IMPACT LLS location error and detection efficiency when compared to power line fault data from the nearby winter lightning region (N36.375 - 37.375 / E137.75 -138.875)

| Number of lightning faults | Number concurrent with lightning location data | Detection efficiency | Location error (Average) |
|---|---|---|---|
| 132 | 128 | 97.0% | 2.7km |

As stated above, the average location error of the existing IMPACT LLS was 1.1km in the Chubu Electric Power service area but 2.7km in the nearby winter lightning region. This increase in location error on the exterior of the sensor network is a typical characteristic of LLS performance as shown in Figure 3. These results showed that in order to improve the location accuracy in the nearby winter lightning region it would be necessary to install sensors so that this region would be surrounded.

**(2) Examination of the best sensor configuration for the new LS7001 network**

Sensors are normally configured to detect electromagnetic field signals that exceed a certain threshold. However, electromagnetic field signals that are too large can cause the sensor to fail to detect them properly due to over-ranging. Sensors installed too near the target area have a tendency to over-range easily making it difficult to detect lightning strokes that cause serious damage to power equipment. The distance at which over-ranging becomes a problem is dependent on the current value of the lightning and the gain of the sensor. For example, a sensor configured at medium gain starts to have over-ranging problems when the lightning current exceeds 300kA in a stroke detected from a distance of about 100km.

In considering the ideal sensor configuration, we decided to maintain a distance of about 100km between the sensors and to install them so that a 300kA lightning strike to the new power plant would not cause the sensors to over-range. In the end, after considering the surrounding geographic conditions, we decided to install additional sensors at “Niigata” and “Noto”, and to replace the “Nagano” sensor site with one at “Saku”. The simulated location accuracy projection map in Figure 5 was created using the actual lightning current distribution in the region. The proposed sensor configuration is shown in Figure 6.

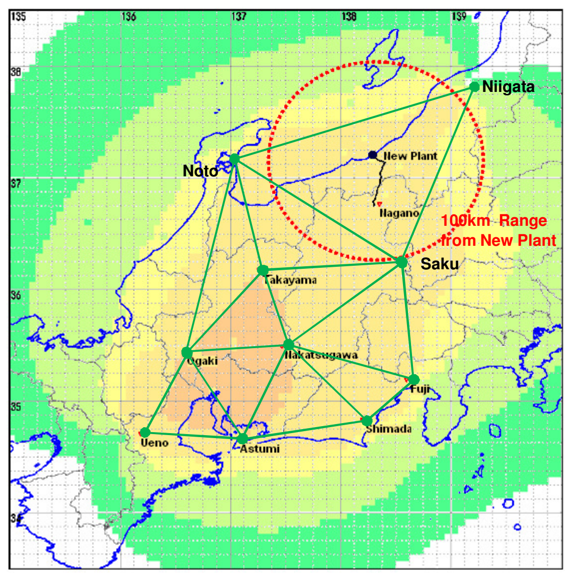



Figure 5: Simulated location accuracy projection using actual current distribution (Location Error: ■: 0 to 0.5 km, ■: 0.5 to 0.75km, ■: 0.75 to 1 km, ■: 1 to 2 km, ■: 2 to 4 km, and □: 4km or more)

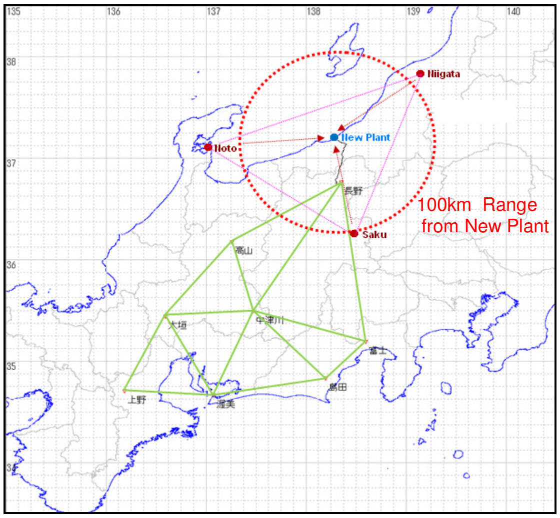



Figure 6: Proposed ten LS7001 sensor network configuration (The green lines show the IMPACT sensor network configuration. The "Nagano" IMPACT sensor was decommissioned and replaced by an LS7001 Sensor at the "Saku" location.)

## 3. EVALUATION OF THE LS7001 NETWORK

### 3.1 LS7001 VS. IMPACT: IMPROVEMENTS IN DETECTION EFFICIENCY

The performance of the LS7001 network was evaluated after completion of construction. Evaluation of the detection efficiency characteristics of the eight sensor IMPACT network and the ten sensor LS7001 network was important, but the two networks did not operate at the same times and the sensor configurations were also not the same. These factors made a simple network comparison impossible. We decided to limit our analysis to the 2.5 month winter periods from December 1st to February 15th of the past three years (see Table 3).

Table 3: Sensor upgrades and lightning location periods of operation

| | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|
| (1) Before upgrading<br>IMPACT sensor x 8 | Location term | ★ | | |
| (2) Middle of upgrading<br>LS7001 sensor x 5<br>IMPACT sensor x 5 | | Sensor upgrading | Location term ★ | |
| (3) After upgrading<br>LS7001 sensor x 10 | | | Sensor upgrading | Location term ★ |

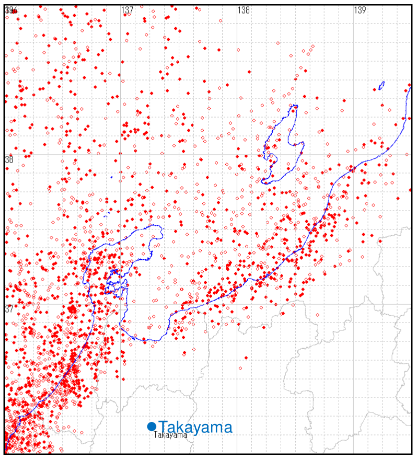
To examine the year to year changes in lightning locations, we first investigated the lightning location distribution in an area near the Japan Sea coast from north latitude 36.0 to 39.0 degrees and from east longitude 136.0 to 139.5 degrees detected by the five IMPACT sensors at Ueno, Takayama, Ogaki, Nakatsugawa and Atsumi in the western portion of the Chubu region. We looked at the lightning detected in winter 2010 before the first upgrade and at the winter 2011 lightning reports after the upgrade process had begun. Those results are shown in Figure 7(1) and 7(2).

In the winter of 2011, the IMPACT network reported 7,071 lightning locations. This was an increase of 3.1 times over the 2,292 locations reported by the network in the same period during the previous year

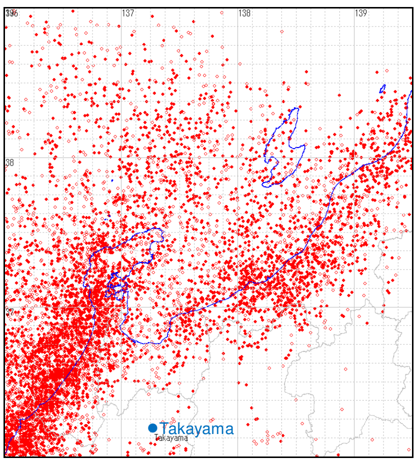
Next, we investigated the lightning location distribution in the same area near the Japan Sea coast after the first phase of the upgrade had been completed. The first five LS7001 sensors that were installed were located at a Noto, Niigata, Saku, Fuji, and Shimada in the northeast portion of the Chubu region. We compared data from the interim network consisting of five IMPACT-ES sensors and five LS7001 sensors to data from the eight sensor IMPACT network (6 IMPACT-ES and 2 IMPACT-ESP). Those results are shown in Figures 8(1) and (2)).

The number of lightning locations reported by the LS7001/IMPACT-ES network in winter 2011 was 5.1 times the number of locations reported by the IMPACT network in winter 2010, 17,313 as opposed to 3,403. The data shown in Figure 7 clearly indicated that there was much more lightning in the second year, but the dramatic increase in locations reported by the LS7001/IMPACT-ES network shows the effectiveness of the network upgrade.

The number of lightning locations reported by the ten sensor LS7001 network in winter 2012 was 6,307, an increase of 1.85 times over the 2010 winter data collected before the upgrade began. This number is low compared to the LS7001/IMPACT-ES network data from the winter 2011. The authors concluded this difference was caused by year to year fluctuations in lightning occurrences rather than by the changes in the sensor type. (See Figure 8(3) and Table 4).

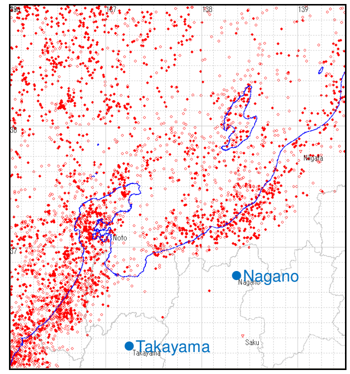



(1) Winter 2009/2010
Before the upgrade
Sensor configuration: ●IMPACT-ES x 5
2,292 lightning locations reported

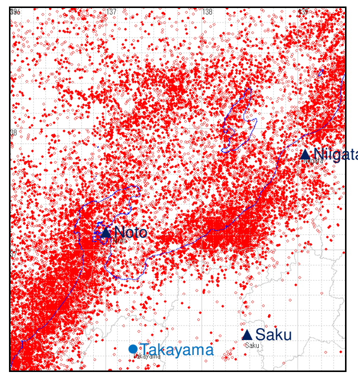



(2) Winter 2010/2011
Halfway through the upgrade
Sensor configuration: ●IMPACT-ES x 5
7,071 lightning locations reported

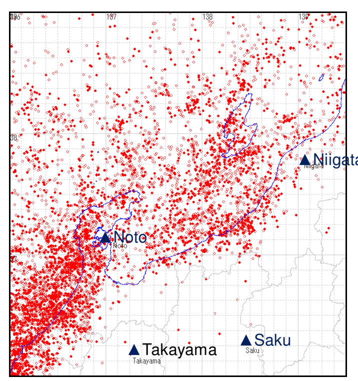
Figure 7: Winter 2009 and Winter 2010: Lightning Locations Reported by the Same IMPACT-ES Sensors (Near the Coast of the Sea of Japan)




(1) Winter 2009/2010
Before the upgrade
Sensor configuration: ●IMPACT-ES x 6
●IMPACT-ESP x 2
3,403 lightning locations reported




(2) Winter 2010/2011
Halfway through the upgrade
Sensor configuration: ▲LS7001 x 5
●IMPACT-ES x 5
17,313 lightning locations reported




(3) Winter 2011/2012
Upgrade completed
Sensor configuration: ▲LS7001 x 10
6,307 lightning locations reported

Figure 8: Lightning locations reported during each stage of the network upgrade process (near the coast of the Sea of Japan)

Table 4: Lightning locations reported during the steps of the upgrade process (Near the coast of the Sea of Japan in Winter)

| Period | Reference Network (Sensor Type) | Operational Network (Sensor Type) |
|---|---|---|
| 1. 2009-2010, Winter (Before upgrade) | 2,292 (IMPACT×5) | 3,403 (IMPACT×8) |
| 2. 2010-2011, Winter (Midway through the upgrade) | 7,071 (IMPACT×5) | 17,313 (IMPACT×5, LS7001×5) |
| 3. 2011-2012, Winter (Upgrade Completed) | | 6,307 (LS7001×10) |
| Rate of increase Period 2 vs. 1 | 3.1 times | 5.1 times |

### 3.2 CHANGES IN LIGHTNING DETECTION EFFICIENCY: ORIGINAL VS. UPGRADED NETWORK

As shown above, the number and distribution of lightning events varied by year. In order to effectively evaluate the differences in sensor performance, we selected data from periods of time when both types of sensors were operating simultaneously and compared their relative detection capability. The five sensors (Noto, Niigata, Saku, Fuji, and Shimada) in the northeast area of the Chubu region were upgraded to LS7001's in 2010. The five sensors (Ueno, Takayama, Ogaki, Nakatsugawa, and Atsumi) in the southwest area were upgraded in 2011. For this analysis, we used lightning location data of the period from May to September, 2011 in the area from 33.5 to 38.5 degrees north latitude and 136-139.5 degrees east longitude when summer lightning occurs across the entire Chubu region.

**(1) Relative detection efficiency comparison**

The relative detection efficiency, the percentage of lightning location solutions in which each sensor participates, was calculated relative to distance for each sensor in the combined network of five LS7001 sensors and five IMPACT sensors that was operating during this period. One example showing the comparison of the Atsumi IMPACT sensor and the Shimada LS7001 sensor is shown in Figure 9. The relative detection efficiency falls off as distance from the lightning event increases, but the rate of the fall in detection efficiency of the Shimada sensor is slower. The average relative detection efficiency of the Shimada sensor out to a distance of 500km was 61% compared to 54% for the Atsumi sensor. This demonstrates the LS7001 sensor's ability to detect more lightning from a greater distance than the IMPACT sensor.

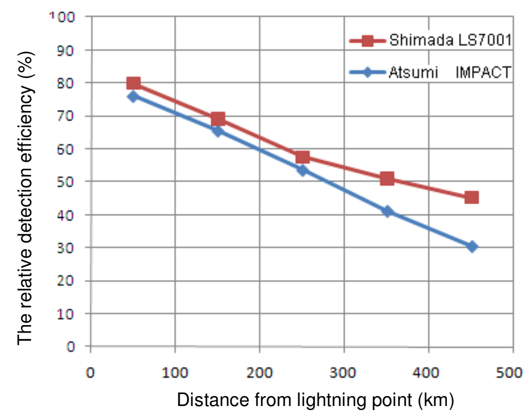



Figure 9: The relative detection efficiency of the Shimada LS7001 sensor and the Atsumi IMPACT sensor

**(2) Network Comparison: IMPACT vs. LS7001**

Data from this period when both the five LS7001 and the five IMPACT sensors were operating was reprocessed as two independent networks. Lightning locations reported by the LS7001 network were compared with results from the IMPACT network. Figure 10 shows the two five sensor networks and the analysis area.

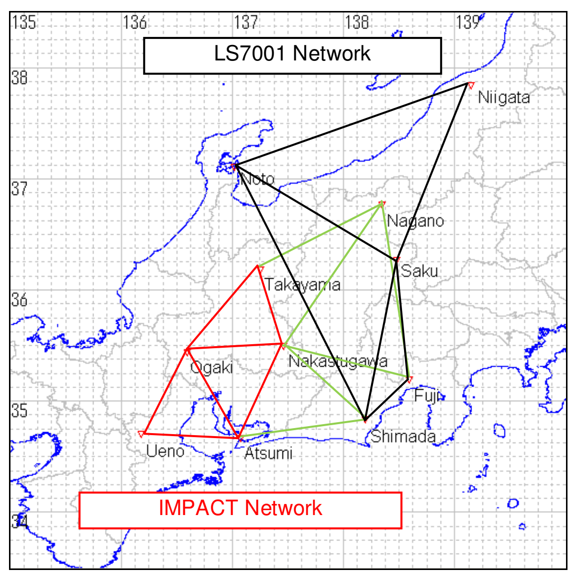



Figure 10: The IMPACT and LS7001 networks and the area studied

The LS7001 network reported 211,593 lightning locations and the IMPACT network reported 151,770 events. Figure 11 and Table 5 show the results from the two networks relative to the lightning current strength.

This shows that the number of lightning events reported by the LS7001 network was higher throughout the range of current values. That tendency is more remarkable with large current events. The LS7001 network detected 1.4 times the number of events reported by IMPACT network across the entire range of current, 211,593 vs. 151,770. However, for events with current values of 100kA or greater, the LS7001 network reported 2.1 times the number detected by the IMPACT network, 2,009 vs. 981.

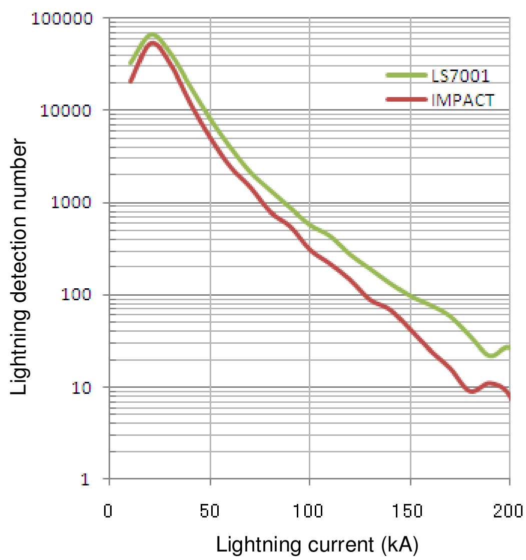



Figure 11: Lightning locations reported, LS7001 and IMPACT networks across a range of current values in 10kA increments

Table 5: Lightning locations reported by the five sensor IMPACT and five sensor LS7001 networks during the summer 2010 halfway through the upgrade

| Network Sensors | All | 100kA or more |
|---|---|---|
| IMPACT×5 | 151,770 | 981 |
| LS7001×5 | 211,593 | 2,009 |
| Rate of increase (LS7001/IMPACT) | 1.4 times | 2.1 times |

**3. SUMMARY AND FUTURE WORK**

In conjunction with the construction of a new power plant and a new transmission line outside the Chubu Electric Power service area, we constructed an LLS network during 2010 and 2011 consisting of ten LS7001 sensors. The new network has two more sensors than the IMPACT network it replaced. Sensor locations were selected to surround the new power plant at a distance of 100 km or more to ensure that large current events near the new plant and the new transmission line would be detected.

In order to evaluate the lightning location performance of the new LLS, we produced and compared lightning location distribution reports before and after the upgrade in the area near the coast of the Sea of Japan which included the new power plant and transmission line. Although there were changes in the number of lightning events from year to year, it was confirmed that the number of lightning locations increased after the LS7001 sensor network upgrade was completed.

We compared relative detection efficiency, in order to avoid the influence of year to year variances in lightning occurrence and to evaluate the differences in sensor performance. We concluded that the average relative detection efficiency of the LS7001 sensor (Shimada) was 61% out to a distance of 500 km from the lightning location while the same value for the IMPACT sensor (Atsumi) was 54%. In addition, the LS7001 sensor detected 1.4 times more events than the IMPACT sensor across the whole range of current values and 2.1 times more events for lightning strokes with current values of 100kA or more.

It can be supposed that the reasons the LS7001 sensor has higher lightning detection efficiency compared with the IMPACT sensor are the effect of the elimination of dead time and the extension of the lightning waveform discrimination criteria. It can also be supposed that changing the setting of the maximum rise time criteria to 100 microseconds from 30 microseconds for the location of winter lightning contributed to the improvement in detection efficiency. Since we have experienced frequent examples in which the LLS cannot detect lightning events with large currents that cause transmission line faults, the LS7001 whose detection efficiency for large current lightning events has improved greatly, is a very important step forward for us. We are looking forward to improved detection of large current lightning events that cause faults on transmission lines. In addition, we have confirmed that the LS7001 sensor is able to detect more lightning from a greater distance. From this, we are able to conclude that this sensor will be very useful also in a larger network.

It has only been a short time since construction of the new LLS was completed and we have only been able to obtain a short period of winter lightning data. We have not yet been able to do a detailed analysis of the network's location accuracy. In the future, after a sufficient amount of data has been collected, we plan to do a more detailed analysis and to evaluate system performance by comparing lightning location reports with transmission line fault and other ground truth data.

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