

## Dependence of atmospheric electric field on solar activity

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The vertical atmospheric electric field variations depend on the state of the global circuit. Under the fair weather condition, atmospheric electric field directs vertically downward. The direction is due to the electric potential in the ionosphere and the Earth's surface. Thus ionospheric state seems to affect atmospheric electric field.

Kleimenova et al. [2010] examined atmospheric electric field at the time of substorms. They concluded that the deviations of  $E_z$  at high latitudes are the result from an enhanced polar convection or change in the ionospheric potential.

Since the report was established based on high-latitude data, we focused on low-latitude atmospheric electric field variation related with ionospheric state. In this study we analyzed the low-latitude atmospheric electric field  $E_z$  at KAK (G.G. Lat.: 36.2 N, G.G. Lon.: 140.2 E) and solar F10.7 index which is derived from solar radio flux at a 2.8 MHz. The solar F10.7 flux is well known that related with ionization in the ionosphere through solar extreme ultraviolet (EUV) emission. Daily  $E_z$  amplitude for high solar-activity (F10.7 > 100) periods shows higher value than that for low solar-activity (F10.7 < 100) periods. The tendency is predominant in July and August. When solar EUV flux is intense, ionization in the ionosphere are promoted and ionospheric potential becomes higher. We, therefore conclude that potential difference between the ionosphere and the Earth's surface becomes larger and the atmospheric electric field is enhanced during high solar-activity periods.

Keywords: atmospheric electric field, solar activity

## Prediction of Nighttime VLF Signal Amplitude for Mid-and High-Latitude Paths

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The amplitude of Sub-ionospheric Very Low Frequency (VLF) propagation is sensitive to the lower ionospheric. Accordingly, VLF waves have been proposed to study and monitor the lower ionospheric conditions. However the temporal dependence of VLF amplitude has complicated and large daily variabilities in general due to combinations of both effects from above (space weather effect) and below (atmospheric and crustal processes) of the ionosphere. Thus the modelling and prediction of VLF wave amplitude are important issues to study the lower ionospheric responses from various external parameters and to also detect the anomalies of the ionosphere.

In this paper, the NARX (Nonlinear Autoregressive with Exogenous Input) neural network is used as a novel method for predicting daily nighttime averaged amplitude of VLF transmitter signals indicating the ionospheric perturbation around the transmitter-receiver path. The NARX neural networks has a good accuracy in predicting time series data and thus are more suitable for dynamic modelling. The NARX model, which was built based on daily input variables of various physical parameters such as stratosphere temperature, cosmic rays, total column ozone, K-index, AE-index and Dst, possessed good accuracies during the model building. The NARX model for VLF transmitter in Hawaii, USA (NPM) and receiver in Chofu (CHF) Tokyo, Japan (mid-latitude path), which was constructed based on above mentioned. In addition, the high-latitude path from the transmitter in Washington, USA (NLK) to receiver in Chofu (CHF) Tokyo, Japan, which was built as well.

As a result, the constructed models are capable of performing accurate one step (1 day) ahead predictions of the nighttime VLF amplitude from January 1st, 2011 to December 31st, 2013 for NPM-CHF path with the Pearson correlation coefficient ( $r$ ) of 0.93 and with Root Mean Square Error (RMSE) of 2.0 dB and also the results for multi-step ahead 5 days prediction ( $r = 0.86$ ,  $RMSE = 1.88$ ) and multi-step ahead 10 days prediction ( $r = 0.74$ ,  $RMSE = 2.35$ ). Furthermore, result for NLK-CHF path with  $r$  of 0.91 and RMSE of 2.64 dB. In addition, we will demonstrate multi step ahead prediction of daily nighttime VLF amplitude for NLK-CHF paths. We conclude the model built according to the proposed methodology provides accurate predictions of the electric amplitude of VLF wave for both NPM-CHF and NLK-CHF propagation paths.

Keywords: very low frequency, VLF transmitter, nonlinear autoregressive with exogenous input, one-step ahead prediction, multi step ahead prediction

## Lower ionosphere perturbations caused by Hokuriku winter lightning

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Intense electromagnetic pulses (EMP) radiated from lightning discharge could cause heating and ionization in the ionospheric D-region. While theoretical studies show that change in ionization state in the D-region depends on intensity of EMP, there is no clear observational evidence that shows quantitative relationship between them. The purpose of this study is to reveal influence of the CG(Cloud-to-Ground) and GC(Ground-to-Cloud) lightning discharges on the D-region and to confirm theoretical predictions by observation. The change in ionization state in the D-region is detected using perturbation in low frequency (LF) manmade radio waves which propagate in an earth-ionosphere waveguide. For this purpose, LF radio observation system was installed in Takine (Fukushima Pref.) and measured radio signal from JJY transmitter(60kHz) at Mt. Haganeyama. The midpoint of radio propagation path is located over the coast of Hokuriku area. This enables us to investigate Hokuriku winter lightning effect on the lower ionosphere near the 1-hop point of LF radio propagation. Distance between Takine and Mt. Haganeyama is 1045km and the 1-hop theory is well applicable to predict signal phase at the receiver. The LF sub-ionospheric perturbations which are called as early events have been observed from December 12, 2014 to March 31, 2015. World-Wide Lightning Location Network was used to identify lightning location and timing during this period and totally 189 sets of sub-ionospheric perturbation and causative lightning were detected. A peak current of causative lightning which is a proxy of the EMP intensity was derived from LF atmospheric observation at Suzu (Ishikawa Pref.). Charge moments of the lightning were also derived from ELF magnetic field observation at the Syowa station (Antarctica). The charge moments derived were distributed from 200 to 500 C-km and suggest that quasi-electrostatic field was lower than breakdown threshold at the lower ionosphere and was not responsible for producing sub-ionospheric perturbation observed. Modeling studies predict that EMP produced from a CG discharge creates torus-shaped ionization pattern around 90km height above a causative lightning and horizontal scale depends on intensity of EMP. We statistically examined sense of the phase change as functions of strength of EMP and distance of causative lightning from the 1-hop point along radio propagation path. Based on the 1-hop theory, positive and negative changes in the phase correspond to downward and upward shifts of radio reflection height, in other words, increase and decrease in ionization in the lower ionosphere near the 1-hop point, respectively. Result shows that sense of the phase change strongly depends in both strength of EMP and distance of causative lightning from the 1-hop point; (1) phase increase (which correspond to the ionization increase) was found when a distance between a causative lightning and the 1-hop point was within 100km and the peak current was smaller than 200kA. The distance increased up to 150km when the peak currents were larger than 200kA. This shows that ionization area extends further due to more intense EMP. (2) Outside of these distances, on the other hand, the phase decreases (which correspond to the ionization decrease) was found. Intensity of EMP decreases as distance from a causative lightning. When the electric field strength becomes lower than the breakdown threshold, electron attachment rate dominates ionization rate, causing decrease in ionization state. (3) Less occurrence of sub-ionospheric perturbation was found inside the distance of 20km from the 1-hop point compared to the surrounding area. This suggests that EMP does not affect ionization state in the lower

ionosphere just above CG/GC discharge. These results are consistent with the theoretical expectations.

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Keywords: lightning discharge, ionospheric D-region, early event

## Development of a new multipoint observation system for gamma-rays from winter thunderstorm

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Recent observations have shown that winter thunderstorm along the Japan sea radiates gamma-rays with energy extending up to 10 MeV (Torii et al., 2002, Tsuchiya & Enoto et al., 2007). Inside the thunderstorm, electrons are accelerated to relativistic energy by strong electric field. So far, since observations have been performed at a single location, it has been difficult to trace generation, growth, and disappearance of the acceleration region of relativistic electrons. In order to reveal this acceleration mechanism, we are planning to build a multi-point mapping system of the gamma-ray radiation which can trace a path of the radiation and can detect a change of gamma ray intensity and spectrum. Since a typical velocity of the winter thunderstorm is about 500 meter per min and a duration of the gamma-ray radiation at a single point is about a few minutes, new observation sites are expected to be about 20 points with their separation of a few kilometers. We have developed a small radiation detector composed of scintillators (CsI, BGO, and plastic) coupled with new data acquisition system using a small computer Raspberry Pi. The detector size is about 30 cm. In 2015FY winter, we set these detectors on the roof at Kanazawa University and one high school at Kanazawa, and started the observation, collecting photon energy and arrival time of individual photons, and environmental temperature. We are planning to increase observation sites. This project has been also supported by fund from an academic crowd-funding.

Keywords: winter thunderstorm, gamma-ray, electric field, electron acceleration

Lighting-induced bremsstrahlung X-rays observed near the leader.

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Energetic radiation, bremsstrahlung X ray in energy range of gamma ray, associated with lightning activities and thunderstorm have been reported. The lifetime of lightning-generated X rays, termed short burst, is in the order of millisecond. These X rays are considered to be generated by bremsstrahlung along the leader, termed short burst. During the winter, the bright short burst with more than 100 millisecond duration was detected on 4 Dec. 2015. In this analysis , we compare radiation data with VLF lightning location data and high speed camera data.

Keywords: Energetic radiation, Winter Lightning, Thunderstorm

## Cloud-to-ground flashes with multiple strokes observed by Broadband Digital Interferometer

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It is known that the overwhelming majority of negative cloud-to-ground flashes contain more than one stroke. Some of them create more than one channel termination to the ground with the spatial separation. This paper discusses the precedent and subsequent leader developments of negative cloud-to-ground flashes mapped by Broadband Digital Interferometer. Seven flashes have multiple terminations out of focused 13 negative cloud-to-ground flashes with multiple strokes observed at Gifu prefecture, Japan in summer 2014. In these observations, whether the subsequent leader deflects from the previously formed channel and creates a new termination or follows the previous channel does not depend on the time interval between strokes. Even the events are observed that first and subsequent leader traverse two channels alternately. The mechanism of multiple strokes is very complicated.

Keywords: lightning discharge, multiple storke, broadband digital interferometer

## Highly time resolved tracking of the torrential rain from lightning data

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Previous studies suggested that there exists a good relationship between frequency of lightning and atmospheric convection or precipitation [e.g. Deierling and Petersen, 2008]. Therefore, lightning data can be used as a proxy for the presence of deep atmospheric convection and precipitation. To monitor time series behavior of lightning activity, it is possible to understand more detailed relationship between the lightning activity and atmospheric convection and it is also possible to predict the distributional area of precipitation.

Our purpose of research is to estimate rain activity by the information of cloud to ground (CG) lightning discharge location. Therefore, we compare the movement of the torrential rain area with the lightning cell by a calculation of a time variation of the CG lightning frequency and that of spatial distribution of lightning.

We analyzed 3,909 events of CG lightning from 14:00, August 11th 2013 to 15:29 (JST) and 3,693 events of CG lightning from 17:30, August 12th 2013 to 19:24 (JST) observed by Japan Lightning Detection Network (JLDN) in Kanto region to estimate the frequency and spatial distribution of CG lightning for 10 min and with 1km square grid. We use the C-band rain radar data provided by the Japan Meteorological Agency (JMA) as the data of rain intensity. The temporal and spatial resolutions of the data are 10min and 1km.

As a result of comparing spatial distribution of lightning with that of precipitation, it is possible that there is a good correlation between the CG lightning distributional area with torrential rain area (>50mm/h) and it is possible that we can estimate the torrential rain area (>50mm/h) to monitor the time variation of the CG lightning frequency and that of spatial distribution of lightning.

We calculated the cross correlation function between the CG distribution at a certain time and that of the one 1 later in order to estimate the motion vector of CG area and we required the luminance centroid to track CG lightning area. We also calculated the cross correlation function between the torrential rain area (>50mm/h) at a certain time and that of the 10 minute later in order to estimate the motion vector of rain area and we required the luminance centroid to track rain area. As a result of comparing the lightning luminance centroids and that of precipitation, we can estimate the luminance centroid of the torrential rain area (>50mm/h) with an accuracy of 2km by using the luminance centroid of lightning distributional area and it is possible that we can estimate the motion of the torrential rain area with highly time resolution by CG lightning data. In this presentation, we will discuss the adequacy of analysis method and our initial result. Also we will consider the relationship between the distributions of the CG lightning frequency and torrential rain area.

Keywords: Lightning, Cloud to ground lightning discharge, Tracking of the lightning cell



## Relationship between charge structure and vertical air motion in a thunderstorm revealed by a phased array weather radar and 3D lightning mapper

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Thunderstorm observation has been conducted in Osaka, Japan, with a use of an X-band phased array weather radar (PAWR) and a 3D lightning mapper, called Broadband Observation network for Lightning and Thunderstorm (BOLT), for further understanding of relationship between electrification mechanism and vertical air motion, which plays an important role in non-inductive charging process. PAWR employs mechanical and electrical scans, respectively, in azimuthal and elevation direction, succeeding in quite high volume scan rate. BOLT is a LF sensor network that receives LF emission associated with lightning discharges and locates LF radiation sources in 3D. BOLT is capable of estimating charge structures removed by both intra-cloud (IC) and cloud-to-ground (CG) flashes. In this presentation, we focus on lightning activity and charge structure in a convective cell recorded on 30 July 2015. The convective cell involved severe lightning activity in 15 minutes and the both IC and CG flash rate (the number of flash per minute) changed drastically within the 15 minutes. We divide the 15 minutes lightning activity into three stages; the first, the second and the last 5 minutes, respectively, are termed developing, mature, and dissipating stages, based on IC and CG flash rates. In the developing stage, IC flash rate increased drastically from a few to about 10 flashes  $\text{min}^{-1}$ . In the mature stage, IC flash rate are quite high and had a peak of 12 flashes  $\text{min}^{-1}$ , while CG flash rate increased gradually. In the dissipating stage, IC flash rate drastically decreased, while CG flash rate had a peak of 5 flashes  $\text{min}^{-1}$ . In the developing stage, updraft in the mid-level (about 7 km) developed into the upper level (10 km or more in AGL). In this presentation, we estimate existence of updraft from Doppler velocity and ascending echo. The echo top of the convective cell increased rapidly. The main positive charge region estimated by BOLT was located around the updraft region in the upper level. In the mature stage, the updraft was further intensified and the echo top reached the tropopause altitude of 14.5 km. The main positive charge region was again located in the updraft of the upper level. In the dissipating stage, divergence at the echo top produced cold downdraft in the rear flank of the convective cell. The cold downdraft descended to mid-level (about 7 km) and suppressed the updraft at mid-level so that the updraft in the upper level was weakened. These observation results indicate a strong relationship between electrification for IC discharges and updraft strength. In the dissipating stage when CG flash rate peaked, main negative and pocket positive charge regions estimated by BOLT were located near the mixture region of the cold downdraft and updraft from the lower level. We speculate that the pocket positive charge region was mainly produced by the collisions between graupel in the downdraft originated from the upper level and the ice pellets ascending from the lower level. These simple speculation support that non-inductive charging mechanism in thunderstorms.

Keywords: lightning, updraft, charge structure

## Study of observational accuracy of non-rotating dual-polarization phased array radar

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At present, a phased array radar (PAR) that has high time resolution (30[sec]) and high spatial resolution (100[m]) has been already developed and under operation in Osaka University. PAR has lower accuracy of observation than dual polarization radar because of using only single polarization. Although the development of the dual polarization phased array radar that has both high-speed scanning and high-precision observation is expected, to maintain a high observation accuracy is difficult because of the effect of deterioration of the antenna characteristics by digital beam forming and reduction of cross polarization discrimination which is performance to distinguish between horizontal pattern and vertical pattern. In order to solve such problems and develop dual polarization phased array radar, we designed three types of array (planar, cylindrical, and hemispherical) and simulated.

By comparing the performance of the three types of array, it is found that the hemispherical array is superior to the others because its shape is facing in all directions equally.

Keywords: phased array radar, dual-polarization, precipitation observation

## Development of a polarimetric phased array weather and adaptive beamforming technique

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Development of a polarimetric phased array weather radar as a subsequent project of the phased array weather radar (PAR) is under discussion. The design of a polarimetric phased array weather radar has been the object of several experimental development. The polarimetric phased array weather radar has significantly advanced the following points. 1) to classify types of precipitation, 2) to provide quantitative estimates of precipitation accumulation, 3) to obtain high spatial and temporal resolution volumetric radar data. 1) and 2) are contributed by a polarimetric sensing technique, and 3) is provided by the digital beam forming techniques in a phased array radar system. In this paper, precipitation radar signal simulations based on the under considering radar concept are carried out to discuss the estimation accuracy of polarimetric precipitation profiles (differential reflectivity, specific differential phase, and copolar correlation coefficient) with two DBF methods that are based on Fourier and minimum mean square error (MMSE) methods. The comparison of the performance of the two methods indicates that MMSE is superior in an observation accuracy because of the effect of a stable and robust main lobe and adaptively suppressed side lobes.

Keywords: weather radar, Phased array antenna

## Development of precipitation attenuation correction technique in a dual-pol radar network

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Dense radar network systems with low power transmitters at X-band has been proposed which can fill in observation gaps in low altitudes and have good accuracy and resolution. An X-band dual polarization radar network is the main stream of weather observation to make rapid scanning at low altitude. The dual polarization products such as differential reflectivity ( $Z_{DR}$ ), specific differential phase ( $K_{DP}$ ) and correlation coefficient ( $\rho_{hv}$ ) provide us with detailed information about drop size distribution (DSD) and rainfall rate estimation.  $K_{DP}$  can be calculated from differential phase  $\phi_{DP}$ .

On the other hand, a weather radar, especially with transmitting short-wavelength pulses, is affected by precipitation attenuation. Various attenuation correction techniques for horizontal reflectivity ( $Z_H$ ) and  $Z_{DR}$  using  $\phi_{DP}$  and  $K_{DP}$  were proposed. However, measured differential phase  $\psi_{DP}$  consists of  $\phi_{DP}$  and backscattered phase shift  $\delta_{co}$ .

Especially at C-, or X-band, contamination due to delta cannot be ignored. Some  $\delta_{co}$  removing techniques were proposed. Scarchilli et al. (1993) suggested recursive algorithm to remove delta from  $\psi_{DP}$  in an individual radar using  $\delta_{co} - Z_{DR}$  relationship. They assumed coefficients in the power-law relationship. However, the relationship actually depends on DSD. In this paper, probabilistic attenuation correction technique based on the Bayesian theory in multiple dual polarimetric radar network, is proposed. The proposed technique considering  $\delta_{co}$  effects also derive coefficients of relationships.

Keywords: meteorological radar, rain

The prediction method of sever hazards(Lightning strikes, Hails, etc.) by using Phased Array Weather Radar(PAWR)

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The prediction method of sever hazards(Lightning strikes, Hails, etc.) by using Phased Array Weather Radar(PAWR) will be presented in this session. Several new prediction techniques are presented.

Keywords: Phased Array Weather Radar, Lightning strikes, Hails