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Anthropogenic EM Noise and EMC

E.1 2009 International Symposium on EMC, Kyoto

EMC'09/Kyoto is organized by Prof. R. Koga, Okayama University, and will be held be held in Kyoto at Kyoto International Conference Center, from June 20th to 24th, 2009. This is the sixth EMC Symposium in Japan, because they have been held every five years since 1984. More than 650 people are expected to attend from 20 countries including Japan, and about 250 technical papers will be presented at the Symposium.

E.2 EMC measurement technology

The studies of EMI antenna and electromagnetic field probe calibration method, electromagnetic field probe using electro-optical crystal, EMI suppression effect by ferrite core, measurement method of lightning surge, evaluation method of RF absorber reflectivity in millimeter wavelength, etc, have been performed in this period. Detail descriptions are presented below.

E2-1. Magnetic field probe using magnet-impedance effect

A high frequency carrier type magnetic field probe, which has high sensitivity and high resolution, called GMI (giant magneto-impedance) probe is proposed [Tan, et al., 2005, 2006a, 2006b; Kayano, et al., 2006]. And its validity of magnetic near field measurements is demonstrated by comparing with a conventional shielded loop coil probe and numerical modeling. The GMI probe can clearly detect current concentration at an edge of a microstrip line, which allows high resolution measurements.

E2-2 Antenna factor of EMI measuring antennas

Radio disturbances emitted from electronic equipment have been measured with an EMI antenna, where the disturbance level is expressed in terms of the electrical field strength. In practical measurements, it is given by multiplying the received voltage by the antenna factor of a measuring antenna used. In order to improve the accuracy of the antenna factors in EMI measurement, new antenna calibration methods have been developed:

(1) Application of the non-linear least squares method has been investigated to reduce the uncertainty due to the ground reflection for the conventional EMI antenna calibration in the frequency range from 30 MHz to 300 MHz [Fujii, et al., 2005a]. (2) An antenna calibration technique was proposed using the Standard Antenna Method for vertical polarization. Based on the results of theoretical investigation, appropriate antenna arrangements were found for the calibration of a biconical antenna [Tsushima, et al., 2005]. (3) A new calculable loop antenna having a 180-degrees hybrid junction was developed to improve the evaluation accuracy of the generated field strength for the Standard Filed Method. The antenna is also applicable to other calibration methods, such as Standard Antenna Method and Three-Antenna Method [Fujii, et al., 2005b]. (4) A new measurement method of a free space antenna factor was developed using a reverberation chamber [Harima 2005a, 2006, 2007a, 2007b]. (5) Methods for calibrating broadband EMI antennas were investigated [Yamanaka, 2005]

E2-3 Calibration of electromagnetic probe

In order to calibrate an electromagnetic probe up to 18 GHz, a method using open-ended waveguides has been proposed as the standard radiators in the frequency range from 500 MHz to 18 GHz [Ishigami, et al., 2002, 2003a]. A calibration facility was established with an anechoic chamber. The uncertainty of the facility was evaluated as ±0.96 dB (500 MHz-8.2 GHz) and ±1.14 dB (above 8.2 GHz) at the confidence coefficient of 95%, respectively. A TEM cell is also used for the calibration below 500MHz. The uncertainty of the facility was evaluated as ±0.74 dB at a

confidence coefficient of 95%

E2-4 Measurements of EMI suppression characteristics of ferrite cores

A major source of the electromagnetic interference in the frequency range below 1000 MHz is disturbance currents flowing on the cables connected to an electronic device. In order to reduce the noise currents, ferrite cores are usually attached to encircle the cables. However, there is no standard method for measuring the EMI suppression characteristics of the core. Hence, a measurement method for the insertion loss and the reflection coefficients of a ferrite core has been studied and developed [Urabe, et al., 2006a, 2006b].

E. 3 Printed circuit board (PCB) and chip level EMC

EMI control technologies are still of prime interest of high-speed electronic device supplier. Engineers who design electronic apparatuses are always more effective, more versatile method of EMI control. Research activities are held in many farms, but results are apt to be closed to the farm. EMC researches are held in a few universities out of more than 100 Universities that have engineering department.

The studies of simulation of undesired noise form PCB, EMI simulation, EMC design, EMC modeling, Design tools, etc, have been performed in this period. Detail descriptions are presented below.

E3-1 Conducted noise currents from PCB

Conductive noise currents flowing out from vehicle-mounted electronic equipment composed of multi-layer printed circuit boards (PCBs) to wire-harnesses form a major disturbance source for vehicle mounted radios. By using actual vehicle-mounted electronic equipment, it was shown that, to reduce the noise current outflow of this type, combining, not separating, the ground layer patterns of a digital circuit and an analog circuit is more advantageous, while the mechanism remains unknown. Based on an idea that this mechanism generates from a change in the amount of common-mode return currents flowing to the ground, noise current outflows were simulated with the method of moment from three types of simple PCBs having different ground patterns, which were validated from measurement of scattering parameters. Furthermore, it was confirmed that slits on a ground pattern allow conductive noise currents to flow out from PCBs [Maeno, et al., 2006]

Electromagnetic disturbances for vehicle-mounted radios can be caused by conducted noise currents that flow out from electronic equipment for vehicles to wire-harnesses. For reducing the conducted noise currents from electronic equipment for vehicles, a simulation and an experiment were made on how ground patterns affect the noise currents from three-layer printed circuit boards (PCBs) with slit-types and plane-type ground patterns. As a result, it was shown that slits on a ground pattern allow conducted noise currents to flow out from PCBs to wire-harnesses. For the PCBs with plane-type ground and one of three slit-type patterns, on the other hand, both the simulation and examination showed that resonance phenomena occur at unexpected low-frequencies. A circuit analysis revealed that the above phenomena can be caused by the imbalance of a bridge circuit consisting of the trace circuits on the PCB [Maeno, et al., 2007a].

Using actual PCBs in electronic equipment for vehicles, Maeno, et al. investigated whether the grounds of digital and analogue circuits should be combined or separated to reduce the conductive noise current from wire-harness connected to the PCBs. As a result, it was shown that, in the FM radio frequency band, a ground without separation gives less noise currents and radiated emissions [Maeno, et al., 2007b].

E3-2 Simulation of undesired noise from PCB

In order to explain the undesired electromagnetic radiation from PCB, FDTD modeling of PCB was implemented. Novel FDTD simulation method using multiple-analysis-space was developed [Kasuga, et al., 2005, 2006a, 2006b]. FDTD modeling of the common mode current by a trace placed near the PCB edge was performed [Tanaka, et al., 2005]. It is demonstrated that the common

mode current increases as the trace is placed closer to the PCB edge and that a guard band is effective for suppression of the common mode current. These results can serve as design guidelines.

E3-3 Characteristic of EM radiation at Gigahertz Frequency and Its Prediction

It has been demonstrated that a common-mode (CM) current can dominate the EMI processes up to 1GHz, despite the fact that a CM current is smaller than a differential-mode (DM) current. Although the CM current decreases above a few gigahertz, near and far electric fields increase as the frequency becomes higher. It was demonstrated that the DM component should be taken into account for EM radiation at gigahertz frequencies. [Kayano, et al., 2005a, 2005b, 2005c, 2005d]

An equivalent circuit model for predicting EM radiation from a PCB driven by a connected feed cable was proposed and demonstrated [Kayano, et al., 2006]. The equivalent circuit model is based on consideration of concepts of CM antenna impedance and distributed constant circuit to the conventional mechanisms of current- and voltage-driven. The proposed model can predict and explain frequency response of CM current with engineering accuracy, and also express the intermediate state of the current-driven and the voltage-driven.

E3-4 EM Radiation from a PCB with Plural Signal Traces

To provide basic considerations for the realization of methods for predicting the EM radiation from a PCB with plural signal traces driven in the even-mode, the characteristics of the EM radiation resulting from two signal traces on a PCB are investigated experimentally and by numerical modeling [Kayano, et al., 2005, 2006]. The frequency responses in the two signal trace case can be identified using insights gained from the single trace case. Although crosstalk ensues, the rule for PCB design is to keep two high-speed traces on the interior of the PCB whenever possible, from the point of view of EM radiation. An empirical formula to quantify the relationship between the positions of two traces and CM current is provided and discussed by comparing four different models. Results calculated with the empirical formula and FDTD modeling are in good agreement, which indicates the empirical formula may be useful for developing EMI design guidelines.

E3-5 EM Radiation from Interconnected PCBs

To understand the electromagnetic (EM) radiation from interconnected PCBs by a cable, the characteristics of the EM interference of test model PCB are investigated by experiment and numerical modeling [Kayano, et al., 2007a, 2007b]. Comparing the cases with and without the interconnection, the ground plane of the interconnected PCBs and the interconnection cable are dominant radiation factor in the lower frequencies. These factors construct large common-mode antenna. On the other hand, the total EM radiation at GHz frequencies is simply determined by the differential-mode current on the signal trace, and cross-talk current on the victim traces. The DM current on the signal trace can be predicted by transmission line theory.

E3-6 EMI Simulation and EMC design of PCB

Problems to control electromagnetic noise radiated from digital electronic devices have been pursued in the groups of Koga, Inoue, Kami, Kuwabara, Schibuya, and some other. A concise electromagnetic model of the power-bus in a multi-layer PCB has been developed utilizing a cavity-mode model together with the segmentation method. Practical speed was enhanced by 400 times than traditional methods, which is useful as a powerful tool in designing PCBs in terms of turn-around time and scale of computation. Models of electric and magnetic coupling on gaped power bus structures and effects of via inductance on split power/ground planes were also investigated. A method to evaluate common-mode excitation on PCBs was demonstrated with practical PCBs having guard traces. The evaluation model is called “imbalance difference model”. Accuracy of the models has been experimentally examined.

(1) TDR analysis of EM radiation from a bend

Discontinuity such as a bend in a micro-strip line is known as one of major radiation sources. The total radiation from the micro-strip line is, however, being generally investigated because of

the difficulties in identifying the radiation from some specific location. In this study, paying attention to the feature of TDR (Time-Domain Reflectometry) measurement, an attempt has been made to extract the radiation only from the bend in a micro-strip line. Such an approach is useful in understanding its radiation mechanism. As a result, it has been founded that the larger the bend angle is, the larger the radiation power becomes. The radiation power achieved 3.5% at maximum when the bending angle was 90^o at the frequencies below 1 GHz. (J. Wang and O. Fujiwara, 2005)
(2) Coupling Mechansim of Digital IC

The radiated susceptibility of a microstrip line with a digital IC has been investigated. A circuit approach was used by converting external incident electric and magnetic fields into equivalent current and voltage sources, respectively, and the interference voltages induced at IC pins were simulated by using a circuit simulator. As a result, it has been found that the digital IC exhibits a higher susceptibility for the magnetic field coupling compared to the electric field coupling (J. Wang and K. Kuwabara, 2007).

Resonance in the power-ground plane of PCB is the prime concern when the EM noise is discussed. A novel method to quickly calculate the effect in terms of transfer impedances between separated ports/vias[Wang, et al., 2004, 2005a]. Which was further extended for gapped power bus[Wang et al. 2005b]. Triangular profile of PCB has become possible to treat by it[Wang et al, 206]

E3-7 Modeling of EMC characteristics of digital IC/LSI

The objectives of the EMC modeling of digital circuits are extended to LSIs as noise driving sources, and linear macro-models of LSIs, called LECCS models, have been developed in Prof. Koga's group. Simulation performance of a model for core logic circuits, LECCS-core, and a model for drivers, LECCS-I/O,. The LECCS-core model is quite similar to the model ICEM which was proposed by French research group, and collaboration to establish an unified standard model for EMC simulation has been started. The field of research is going into the inside of LSI to estimate the noise current which drives PCB. Increase of frequency range requires this change.

E3-8 Suppression of EM radiation

In order to suppress the undesired electromagnetic radiation from a PCB, new PCB structure and shielding technique are investigated with FDTD modeling and experimentally [Kayano, et al., 2005; Tanaka, et al., 2006]. A guard-band structure as a method for suppressing the EM radiation from a PCB was proposed and demonstrated. A signal trace is located between two ground traces (guard-band: GB). The shield structure is effective for suppressing the CM current at lower frequency. However, structures in which a conductive plate exists near the signal trace yield resonances with high level peak of CM current on near and far-field. On the other hand, the guard-band structure is more effective than other structures for suppressing the EM radiation in the considered frequency range. Therefore the guard-band will be effective for high-density PCB packaging with high-speed traces.

Confinement of EM noise inside PCB is intended by applying the periodic structures in the power and ground plane, which realizes the band-gap as appears in a crystal. Toyota[2006] has proven its effect.

E. 4 EMC problem related telecommunication system

The studies of telecommunication system using UTP cables, evaluation method of telecommunication system using APD (Amplitude Probability Density), interference caused by microwave oven, EMC evaluation method of UWB system, EMC problems caused by PLC, interference from PCs having dithered clock systems, disturbance for the radio system in LF band, etc, have been performed in this period. Detail descriptions are presented below.

E. 4 EMC problem related telecommunication system

E4-1 APD measurement

Measuring the amplitude probability distribution (APD) of a disturbance has been shown to be a promising method of defining emission limits for protecting digital wireless services. The correlation of disturbance APD to the bit error probability (BEP) of disturbed wireless systems was demonstrated theoretically and experimentally for modulating schemes including spread spectrum [Gotoh, et al., 2005a]. The theory was extended for evaluating the BEP of coded OFDM systems by introducing multichannel APD measurement [Gotoh, et al., 2007a]. A prototype system has been successfully developed realizing real-time measurement of multichannel APD [Gotoh, et al., 2007b]. Theoretical investigation was made on the method and conditions for converting a disturbance APD measured at one frequency to be valid for another frequency [Matsumoto, et al., 2007b]. Application of APD measurement was proposed to the CISPR compliance test of radiated disturbances from microwave ovens [Gotoh,et al., 2005b]. A method was proposed for evaluating the accuracies of APD measuring instruments [Gotoh, et al., 2006].

E4-2 Interference caused by microwave oven noises

Leakage of EM waves from microwave ovens may cause unwanted interference to wireless LAN systems using the 2.4-GHz band. An FM-AM model of oven noise has been developed, and employed to evaluate degradation in the transmission quality of DS-SS (direct sequence spread spectrum) WLAN (wireless LAN) systems interfered with the oven noises [Matsumoto, et al., 2005a]. Band-limited characteristics of oven noise were discussed [Matsumoto, et al., 2005b], and the results were applied to develop a new reduction method of oven interference in DS-SS WLAN systems by means of adaptive filters [Matsumoto, et al., 2005c].

E4-3 UWB (Ultra wide-Band) systems

In order to evaluate peak radiating power from a UWB (ultra wideband) device accurately, a waveform reconstruction method of the electric field emitted by a UWB device was developed based on the time-domain measurement by introducing a compensation technique of waveform distortions caused by the receiving antenna [Ishigami, et al., 2005a]. A measurement system was developed for monitoring electromagnetic field distribution in the UWB frequency band [Ishigami, et al., 2006]. A new method has been proposed and demonstrated for evaluating the interference between the UWB and the wireless LAN by using the GTEM cell [Yamada, et al., 2007].

E4-4 Interference from PCs employing spread spectrum clock systems

Recent electronic devices, such as PCs (personal Computers), usually employ SSC (Spread Spectrum Clock) techniques to reduce the peak spectral amplitude of their radiating clock harmonics by modulating the clock frequency. Measurement was conducted for investigating two-dimensional distribution of frequency modulated noise current on a PC chassis [Marubashi, et al., 2006]. Investigations were made on the effect of the modulating parameters of SSC on the reduction in spectral amplitude of clock harmonics [Matsumoto, et al., 2005d, 2005e, 2006a]. The impact of frequency modulated harmonics on wireless systems was analyzed for Bluetooth [Murakami, et al., 2005, 2006a], MB-OFDM UWB [Murakami, et al., 2006b, 2006c], and OFDM based WLAN [Shimizu, et al., 2005], [Matsumoto, et al., 2006b, 2007a]. It was found that frequency modulated clock harmonics in many cases degraded the transmission performance of such wireless systems more significantly in comparison with unmodulated ones.

E4-5 EMC problem related PLC (Power Line Communication) system

The increase speed of power line communications may affect existing wireless communication system mainly in HF band. To cope with this problem, the effect of buildings on the attenuation in the electric field was investigated by numerical calculation assuming a model of indoor PLC system and typical structures and materials used for buildings in Japan [Ishigami, et al., 2007].

E4-7 Investigation of disturbance for LF band

The Japan Standard Time signal is transmitted at the frequency of 40 kHz and 60 kHz. Electromagnetic disturbances were measured and their statistical properties were investigated in the frequency band [Iwama, et al., 2006, 2007].

E. 5 EMC test facilities

The studies of test methods using rotating electromagnetic fields, correlation between GTEM cells and anechoic chambers, evaluation methods of reverberation chamber, etc, have been performed in this period. Detail descriptions are presented below.

E5-1 Immunity/susceptibility test method

In order to clarify immunity/susceptibility characteristics against radio-frequency electromagnetic fields, a new test method of using electromagnetic fields two-dimensionally rotating at a very low rate was proposed by Prof. Kami's group, which demonstrated the characteristics depicted in visualized three-dimensional map. They also applied the method to a four-septum TEM cell.

E5-2 GTEM Cell

A GTEM (gigahertz transverse electromagnetic) cell is used for immunity and emission tests. The correlation between the immunity-test result in a GTEM cell and that in an anechoic chamber was examined theoretically [Ishigami, et al., 2001, 2003b]. The average electric fields of the EUT surfaces in a GTEM cell and an anechoic chamber were calculated using the FD-TD method in order to evaluate a suitable installation and size of EUT in the GTEM cell. When the size of EUT was 10%, 20%, or 30% of the septum height, the difference in both the test result of the GTEM cell and the anechoic chamber was expected to be about 1dB, 2dB, or 2-3dB, respectively. Moreover, when the EUT surface approached the septum and floor conductor, the difference increased.

E5-3 Reverberation chamber

Statistical properties of the transmission characteristics in a reverberation chamber were analyzed theoretically and experimentally [Harima, 2005b]. The results were applied to developing a new technique to measure the radiating power of wireless devices in a reverberation chamber [Sugiyama, et al., 2005], [Harima, et al., 2005c].

E.6 ESD and system level EMC

The studies of evaluation method of system level EMC, geospace environment simulator, meta -material type RF absorber, etc, have been performed in this period. Detail descriptions are presented below.

E6-1 ESD measurement

The studies on human electrostatic discharges (ESDs) and ESD generators simulating the human ESD, which is being used for standard immunity testing prescribed by the International Electro-technical Commission (IEC), have been conducted in this period by Prof. Fujiwara's group. Detail descriptions are presented below.

(1) Measurement of discharge currents from human ESDs

Discharge currents through a hand-held metal piece from a charged human body were measured with respect to approaching speeds and charge voltages. A circuit approach for calculating the discharge current has also been given. As a result, it was shown that in case of 300 V charge voltage, the current waveform is not affected by the metal piece approaching speed, while in case of 800 V charge voltage, the fast approach gives the higher current peak. These current waveforms can be predicted from the time invariant spark resistance and the measured frequency characteristics of human body impedance seen from a hand-held metal piece [Taka, et al., 2005].

A method was presented for estimating the voltage waveform of a spark from the measured discharge current through a hand-held metal piece from a charged human body, which exhibited the

presence of arcs following the spark. In view of the arc and a time-varying resistance based on a spark resistance formula, an improved circuit model was given in order to calculate the discharge current in relation to the charge voltage of a human body [Mori, et al., 2005a].

ESD events due to metal objects electrified with low voltages give a fatal electromagnetic interference to high-tech information equipment. In order to elucidate the mechanism, with a 6-GHz digital oscilloscope, the spark current was measured through a hand-held metal piece from a charged human body, and proposed a current calculation model. Taka, et al. investigated the properties of a spark discharge itself through a hand-held metal piece from a human body electrified with low voltage below 1000 V. From the measured discharge current waveform and the gap voltage calculated from the above-mentioned current calculation model, the gap resistance with respect to time was derived, and the gap length was estimated using a spark resistance formula. As a result, it was shown that for the charge voltage from 200 V to 1000 V, the gap length approximately increases with the charge voltage, while the corresponding gap breakdown field is almost kept constant. The findings were supported by the experimental results that other researchers obtained with their different set-ups consisting of metal electrodes [Taka, et al., 2006a].

The discharge currents due to air discharge through a hand-held metal piece from a charged human-body with respect to charge voltages below 1000 V were measured. The gap breakdown fields were thereby estimated, which were validated from the Paschen's law and other researcher's experimental result [Taka, et al., 2006b].

A method was presented for deriving a gap breakdown field from the measured discharge current due to collision of a hand-held metal piece from a charged human body. Measurements of the discharge currents were made for charge voltages from 200 V to 1000 V. The corresponding gap breakdown fields were derived, which were validated in comparison with an empirical formula based on the Paschen's law together with other researcher's experimental results [Taka, et al., 2006c].

In IEC 61000-4-2 for electrostatic discharge (ESD) immunity testing, an ESD-gun is used to simulate the ESD events from a charged human body. The gun of this kind injects into a device under test the discharge current through a lumped resistor from a charged lumped capacitor. In actual ESD events from charged human bodies, however, the charge distributed on the body surface is discharged through a spark from the fingertip, and its situation is essentially different from that of the ESD-gun. To understand the behavior of the above-mentioned discharge current, with a 6GHz digital oscilloscope, the discharge current was measured through a hand-held metal piece from a charged human body, and proposed an equivalent circuit model for calculating the discharge current with a time invariant spark resistance. Furthermore, with respect to the approaching speed of the hand-held metal piece, the discharge currents were measured through a metal piece from a human-body with a charge voltage raging from 200V to 1000V, and estimated the resultant voltage waveforms from the above-mentioned equivalent circuit model. Through these results, in conjunction with the metal piece speed, the dependence on the charge voltage of current peak, current rise time, time-varying spark resistance, spark length and breakdown field was shown. It was confirmed also that the spark resistance value at the current peak time enables one to calculate the discharge current, which supports the validity of the previously proposed circuit model [Mori, et al., 2006a].

It has widely been accepted that ESD events due to charged human bodies with low charge voltages below 1000 V cause a fatal electromagnetic malfunction in high-tech information equipment. In order to understand a mechanism of such human ESD events, with a 12-GHz digital oscilloscope, discharge currents were measured through a hand-held metal bar or a fingertip with an aluminum foil attachment from a charged human body with a charge voltage of 600V, and the effect of the aluminum foil size on discharges through a fingertip was examined. In addition, by using an equivalent circuit previously proposed for calculating the discharge currents, the corresponding discharge voltages, measurement of which is basically impossible, were estimated. As a result, it was shown that the hand-held metal bar and aluminum foil attachment produce a one-shot discharge current with steeply rising time shorter than a hundred picoseconds and the corresponding discharge voltage abruptly changing from the charge voltage to certain remaining voltages due to arcs following sparks, and the peaks of discharge currents through a fingertip

increase with the attachment foil size. This suggests that the growth of a spark can be affected mainly by the amount of charges accumulated in the stray capacitances around the fingertip. For the discharge through a fingertip without any aluminum foil attachments, however, the measurement shows that the fingertip produces multiple-shot discharge currents with gently rising time larger than a hundred picoseconds and significantly low amplitudes, which are entirely different from the above cases. This means that the fingertip only could not provide electric energy enough for a spark to grow [Taka, et al., 2007a].

With a 12-GHz digital oscilloscope, discharge currents were measured through a fingertip or a hand-held metal bar from a charged human body with a charge voltage of 600V, and comparison of their discharge waveforms was made in conjunction with the corresponding discharge voltages, which were derived from our previously proposed equivalent circuit model [Taka, et al., 2007b].

A transfer impedance of an SMA receptacle as a wideband measurement electrode being used for discharge currents from a charged human was derived, and its frequency characteristics were measured from 300 kHz to 20 GHz. With a 12-GHz digital oscilloscope, measurement of discharge currents through a hand-held metal bar from a charged human was also made, and thereby the injected currents on the SMA receptacle were reconstructed from the measured transfer impedance [Kagawa, et al., 2007].

(2) Characteristic measurement of discharge currents from ESD generators

An immunity testing method for ESDs is being specified in IEC 61000-4-2, in which the contact discharge of an ESD-gun is being normally specified. Air discharge testing is known to be a severe immunity test compared to the contact discharge testing, while the discharge current injected is not well reproduced. Grasping the behavior of the current injected by the air discharge would be helpful in establishing the worst-case ESD immunity testing. Mori, et al. previously measured the discharge currents for air discharge testing onto the IEC recommended current transducer with a commercially available ESD-gun, and showed that there exists a specific relationship of $I_p \cdot t_r^{\zeta}/V_C$=constant ($\zeta$=0.75), between rise time t_r and current peak I_p. The current transducer, however, has frequency dependent transfer impedance, which should affect the measured current waveform. Mori, et al. investigated if the above-mentioned specific relationship can be obtained for air discharge of an ESD-gun onto a ground assumed for a metal enclosure of electronic equipment under test. A method was presented for estimating the discharge current from simultaneously measured magnetic fields with two magnetic field probes regardless of the distance between the gun discharge-point and the probe position, which was validated for contact discharge of an ESD-gun to a SMA connector. With this method, the discharge currents injected onto a ground for air discharge testing of an ESD-gun with intentionally fast and slow approaches were estimated. As a result, it was confirmed that there is a specific relationship between rise time t_r and current peak I_p of $I_p \cdot t_r^{\zeta}/V_C$=constant with ζ=0.57 independent of charge voltages and gun approaches [Mori, et al., 2005b].

ESD testing is prescribed in the IEC 61000-4-2, which is conducted by injecting the transient current through contact /air discharge of an ESD-gun. The current calibration in the IEC standard, however, is being made for the contact discharge because the current waveform injected through the air discharge is greatly affected by a gun approaching speed. With two kinds of commercially available ESD-guns, therefore, the transient currents were measured for the air discharge gun with arbitrary approaching speeds. As a result, it was shown that a similar specific relationship holds between the rise-time and current peak for each ESD-gun despite the poor reproducibility of the current waveform, which is also supported by other researcher's finding for the air discharge of a charged metal spheroid [Mori, et al., 2005c].

By testing discharge current of ESD guns on both discharged at contact and in air, their relationship was examined between current peak/rising time and charging voltage. As a result, it was found that the discharge in air had little effect on the discharge current of approaching speed at less than 1 kV, and that it had higher peak and shorter rising time than those of the contact discharge [Mori, et al., 2005d].

According to the IEC 61000-4-2 for ESD immunity testing, an ESD-gun with charge voltages above 2 kV is used to inject a discharge current onto a device under test. The current waveform is

prescribed in the IEC standard for contact discharge, but is not specified for air discharge due to its poor reproducibility, although the air discharge gives a severe immunity testing. Furthermore, it is well known that ESD events with low charge voltages below 1 kV cause serious failure to high-tech equipment, while its mechanism remains unknown. In order to clarify the severity of low voltage ESD events, using a 12-GHz digital oscilloscope, current waveforms through air discharge of the ESD-gun with charge voltages from 200V to 1 kV were measured. As a result, it was shown that the current peak and rise time become higher and shorter, respectively, in comparison with those for contact discharge, whose tendency was almost the same as the results for charge voltages below 1 kV previously obtained with a 6-GHz digital oscilloscope. It was also shown that the rise time measured for charge voltages below 500 V reaches the limit of measurement (35 ps) [Mori, et al., 2006b].

By using a 12-GHz digital oscilloscope, discharge currents were measured for air discharge of an ESD-gun with charge voltages below 1 kV, and demonstrated that the rise time reached the limit of measurement. Based on the Gaussian response of the oscilloscope, the rise time limit was investigated [Mori, et al., 2006c].

Measurements were made in the frequency range from 300kHz to 6GHz of the transfer impedance of a commercially available calibration target used for the immunity testing against ESDs that the IEC prescribes, and thereby the waveforms of discharge currents injected onto the target were reconstructed from their observed output voltages for contact and air discharges of an ESD generator with a charge voltage of 2kV. As a result, it was confirmed that the transfer impedance has an absolute value of almost 1 Ω at frequencies up to 6 GHz, while resonance phenomena were observed at frequencies around 2 and 5 GHz. This result has demonstrated that the reconstructed discharge current waveforms agree well with those of the observed voltages for the contact discharge and air discharge with slow approach, producing the current with a rise time of almost 1 ns, while the reconstructed current has a slightly small peak and gentle rising part in comparison with those of the observed voltage for the air discharge with fast approach, which gives the current within a rapid rise time of a hundred pico-seconds [Taka, et al., 2007c].

E6-2 Equivalent circuit model for human ESD

A circuit approach for calculating the discharge current through a hand-held metal piece from a charged human body has been proposed by Prof. Fujiwara's group. It has been demonstrated that the current waveforms can be predicted from the time variant spark resistance and measured frequency characteristics of the human body impedance [Fujiwara, et al., 2001a, 2003a].

E6-3 ESD contact ad air discharge measurement

Measurement was made by Prof. Fujiwara's group for the discharge currents injected onto the Pellegrini target for the contact air discharge of a commercially available ESD-gun with respect to its approaching speed to the target. It was found that the fast approach of the ESD gun provides a sharp current with a steeper rise-time and a higher peak, while the slow approach gives a gentle current with the shorter rise-time but lower peak compared to the case for the contact discharge. It was also found that there exists a specific relationship between the rise-time and the peak current normalized to the charge voltage regardless of the approaching speed of the ESD gun [Fujiwara, et al., 2001b, Fujiwara, et al., 2004].

E6-4 FDTD simulation of contact discharge by an ESD-Gun

The electromagnetic noise caused by an electrostatic discharge (ESD) is a major source of malfunction to high-tech equipment. The ESD testing, therefore, is being specified in the IEC61000-4-2, which prescribes the current waveform from an ESD gun through a IEC recommended current detector (Pellegrini calibration target). This IEC current waveform, however, does not always correspond to the one injected onto an actual device for ESD testing. Prof. Fujiwara's group simulated a contact discharge to ground plates using our previously developed FDTD model of an ESD gun. The induced voltages through a magnetic field probe were simulated when the discharge current was injected directly to the ground plate in contact with an ESD gun, whose results were confirmed with respect to the ground plate sizes experimentally [Fujiwara, et al.,

2002, 2003b].

E6-5 Safety evaluation for stochastically varying electromagnetic fields

The cumulative amplitude probability distributions (APD) of leaked electric fields in fusion experimental facilities were measured and an approach to derive their time-average from the measured APD was proposed [Wang, et.al., 2004]. The statistically averaged electric field showed fair agreement with the time-averaged electric field during 6 minutes being specified in the safety guidelines. This finding suggested the usefulness of the APD measurement in lieu of the field measurement during a 6-minute period because the APD can be obtained for a time period much less than 6 minutes.

E6-6 Geospace environment simulator

In order to make quantitative evaluation of electromagnetic environment around spacecraft, three dimensional electromagnetic particle simulations are being performed using 125 nodes (2 TB Memory) of the Earth Simulator System, reporting various physical processes induced by emission of heavy ions in electric propulsion.

E6-7 Application of meta-material to EM wave absorber and shielding material

Meta-material is the material which can control the dielectric constant and the magnetic permeability. At the special condition, the real part of the dielectric constant and the magnetic permeability are negative. This phenomenon makes the flexibility of a design for EM-absorber and shielding material.

Metamaterial–based EM wave absorbers have been proposed and developed for the use of EMC applications. A new concept of "Equivalent Transformation Methods of Material Constant" (ETMMC) [Kotsuka et al. 2004,2005,2006a,2006b] has been proposed, and " EM-wave absorber based on Integrated Circuit Concept" [Kawamura 2006, Kotsuka 2006c] have been developed. In the course of these researches, new metamaterial EM-wave absorbers have has been proposed. These metamatrial EM-wave absorbers are based on the concept of "autonomous control system of living cell" (ACMM) which can change the material constants by computer control [Kotsuka et al. 2006d, 2007a,2007b].

Natural EM Noise

E.7 Lightning

Study in Prof. Kawasaki's group (This section is carried over from the former report)

Thunderstorms observed by TRMM/PR and LIS have been investigated, and Lightning Research Group of Osaka University (LRGOU) has unveiled several interesting features.

Correlation between lightning activities and the snow depth of convective clouds may follow the power-five law. The power five law means that the flash density is a function of the snow-depth to power five. The definition of snow depth is the height of detectable cloud tops by TRMM/PR from the climatological freezing level, and it may be equivalent to the length of the portion where the solid phase precipitation particles exist. This is given by examining more than one million convective clouds, and we conclude that the power five law should be universal from the aspect of the statistic.

Three thunderstorm active areas are well known as "Three World Chimneys", and those are the Central Africa, Amazon of the South America, and South East Asia. Thunderstorm activities in these areas are expected to contribute to the distribution of thermal energy around the equator to middle latitude regions. Moreover thunderstorm activity in the tropical region is believed to be related with the average temperature of our planet earth. That is why long term monitoring of lightning activity is required. After launching TRMM we have accumulated seven-year LIS observations, and statistics for three world chimneys are obtained. We have recognized the additional lightning active area, and that is around the Maracaibo lake in Venezuera. We conclude that this is because of geographical features of the Maracaibo lake and the continuous easterly trade

wind.

Lightning Activity during El Nino period is another interesting subject. LRGOU studies thunderstorm occurrences over west Indonesia and south China, and investigates the influence of El Nino on lightning . We compare the statistics between El Nino and non El Nino periods. We learn that the lightning activity during El Nino period is higher than non El Nino period instead of less precipitation on the ground during El Nino period. Since we expect the strong correlation between precipitation and lightning activity, the results seem to be against the conventional common sense. However analyzed results for these two areas show no contradictions, or we can say that the results are exactly same from the aspect of statistics. The meteorological comprehension is still remained.

Lightning Research Group of Osaka University (LRGOU) has been working for a novel technique of VHF Broadband Digital Interferometer (BDITF) to monitor thunderstorm activity and to image lightning channels for these ten years. The VHF BDITF has been improved to be a quasi operating system, and LRGOU has equipped the BDITF in Korea, in Australia and at four sites near central Japan. LRGOU controls these BDITFs through internet, and conducts remote and continuous monitoring of lightning activity.

The BDITF antenna is capacitive, which bandwidth is from 25 to 100 MHz including amplifier, and its shape is circular with about 30 cm diameter. The BDITF consists of three antennas, and these antennas are deployed at three apexes of an isosceles right triangle. The length of two sides around the right angle is between 5 to 10 meters, because the antenna spacing is not necessary to be fixed to some required length. These two sides are normally set up to direct to north-to-south and east-to-west. Once we have a lightning flash, a few thousands of VHF impulses are emitted, and the BDITF can detect VHF impulses within about 50 km. The scheme to estimate source location of VHF impulses is based on the Fourier analysis. Received VHF impulses are decomposed into Fourier components by FFT (Fast Fourier Transform). Phase differences for all Fourier components between two antennas output are calculated to estimate the incident angles against the base line of two antennas. Since one unit of BDITF consists of three antennas, two dimensional source locations, azimuth and elevation, can be observed. If we install two sets of BDITF with proper spacing, we are able to have 3-D image of lightning channels.

BDITF observations during winter thunderstorm seasons have been carried out around Mikuni and Kanazawa. Three dimensional images of lightning progressions are observed around Mikuni. The propagation velocity of the negative breakdown is estimated, and it is in the order of ten to power five meters per second. This value is nearly the same of the velocity formally observed by the optical streak camera. The lightning channels with branching are captured, and we learn the excellent capability of BDITF. Possible positively charged region is visualized by detecting negative breakdown during continuing current. The observations around Kanazawa for winter thunderstorms are still ongoing.

An electric filed change and VHF/UHF radiation associated with positive cloud-to-ground (CG) flashes during winter in Japan has been observed, and it can be noticed that the intensity of VHF/UHF radiation increases immediately after a return stroke occurrence. It is well known that VHF/UHF radiation intensity by a negative CG decreases during and after a return stroke, and the strong VHF/UHF emission after the return stroke is believed be peculiar to the positive CG. VHF/UHF radiation due to negative CG flashes is emitted from a tip of leader progression, and a lightning channel imaging is available by VHF/UHF interferometer observations. In case of a positive CG, channel imaging of a VHF/UHF interferometer is not available. To interpret the discrepancy of VHF/UHF source mapping between negative and positive CGs, a theory of “Bi-directional Leader Concept” is introduced. That means VHF/UHF radiation associated with a negative breakdown can be observed for both positive and negative CG, and for a negative CG that is the leader progression tip, and for positive CG that is possible positive charge regions. From this aspect, the location of VHF/UHF radiation source for positive CG mapped by interferometers may be equivalent to the location of positive charge distribution inside thunderclouds. In other words we are able to see the charge distribution by the interferometer. The 3D mapping for positive CG obtained during winter thunderstorm in Japan by means of VHF/UHF interferometer frequently gives a very large volume of source distribution, and its horizontal extension occasionally exceeds ten kilometers. The most possible altitude of the distribution of VHF/UHF source location is

equivalent to or slightly lower than the altitude of -10 degree Celsius. The sources are superimposed on the radar cross section, and it is noticed that sources are rather located in a stratified region instead of a convective region. Though it has been believed that the thundercloud during winter in Japan might be small size because of weak convection, our observations by VHF/UHF interferometer are against the conventional understanding. We have occasionally experienced the MCS like thunderclouds even in winter. The total amount of charge is estimated to be a few hundred Coulombs, and it is supposed that thunderclouds, which cause positive CG during winter in Japan, should be a possible parent thundercloud.

E.8 Lightning and spherics

Ionospheric Alfven Resonances (IARs) as a kind of resonance phenomenon in the ionosphere and mangetosphere, were observed in Kamchaktka, Russia ($L = 2.1$) by Hayakawa et al. [2004], who have reported its statistical results on the spectral resonance structures in the ULF /ELF range from 0.1 to 5.0 Hz on the basis of the long-term observation during 2.5 years. Then, Surkov et al. [2006] have presented a theory for mid-latitude IARs excitation due to electromagnetic waves radiated from the lightning discharges, and have found that nearby thunderstorms in a range of 1000 - 2000 km make a main contribution to IARs. The intensity of Schumann resonance, the global electromagnetic oscilliations, was monitored at Moshiri, Japan and a good correlation was found between the global ground temperature and the Schumann resonance intensity [Sekiguchi et al., 2006]. Ionospheric DC electric fields and plasma density variations associated meteorological phenomena such as tropical storm and typhoon were investigated [Sorokin et al., 2005].

ELF wave phenomena in the Earth-ionosphere cavity, known as Schumann resonance, have been studied in order to monitor the lower ionosphere and global lightning activity. Ando et al. 2005a] have developed an algorithm to deduce the global lightning activity map as an inverse problem to the ELF data observed at a few stations in the world. Anomalous Schumann resonance effects have been found for earthquakes by Hayakawa et al. [2005a], who have found an anomaly in Schumann resonance (e.g., enhancement in the fourth harmonic etc.) in Japan, in possible association with a large earthquakes in Taiwan. They have interpreted that this anomaly is due to the interference between the direct signal from a major lightning source in America and the signal scattered from the Seismo-ionospheric perturbation over Taiwan.

Nickolaenko and Hayakawa [2007] have reviewed the latest works on Schumann resonances and related ELF transient events during the last several years, including ionospheric non-uniformities, the use as a global thermometer, new objects for studies, and new results in old problems.

Nickolaenko et al. [2004] have developed a computer algorithm for accelerating the convergence of the time series computations of the ELF pulsed waveforms propagated in the Earth-ionosphere waveguide.

E.9 Electromagnetic phenomena associated with earthquakes

Seismogenic ULF emissions were detected prior to some large earthquakes ; for example, 2004 Niigata-Chuetsu earthquake [Ohta et al., 2005; Hayakawa et al., 2006a] and 2004 Indonesia Sumatra earthquake [Ohta et al., 2007]. Ohta et al. [2005] performed the direction finding from Nakatsugawa, Japan and found that the observed azimuthal directions are consistent with the epicentral directions of both earthquakes, giving a strong evidence on the precursory ULF emissions.

Some sophisticated signal processings were developed and utilized to detect any weak seismogenic ULF emissions [Serita et al., 2005; Hattori et al., 2006; Ida et al., 2006; Ida and Hayakawa, 2006]. Ida et al. [2006] and Ida and Hayakawa [2006] have applied the fractal (mono- and multi-) analyses to ground-based ULF data to suggest that those fractal analysis are very useful in examining the nonlinear process (self-organized criticality) taking place in the lithosphere.

Hayakawa et al. [2007] have reviewed seismogenic ULF emissions, starting from earlier to the latest results. The most important conclusion from all ULF events reported before, is that there must be a threshold of the possible detection of seismogenic ULF emissions as functions of

earthquake magnitude and epicentral distantce. Also, the generation mechanisms of ULF emissions (microfracturing, electro-kinetic effects etc.) are also discussed.

Hayakawa [2007] has reviewed the subionospheric VLF/LF propagation during earthquakes, and have presented event and statistical studies on the correlation of ionospheric perturbations as seen by VLF/LF and earthquakes with large magnitudes, say with magnitude larger than 6.0. Also, a few possible mechanisms have been suggested and discussed.

A precursor of ionospheric perturbations to the Sumatra earthquake was found in a subionospheric VLF propagation signal [Horie et al., 2007]. Associated with other large earthquakes, an anomalous effect on Schumann resonance was detected. For one of those earthquakes, the anomaly appeared one week to a few days before the main shock [Hayakawa et al., 2005], and the anomaly was numerically modeled [Nickolaenko et al., 2006]. A subionospheric LF and VLF propagation anomaly caused by ionospheric disturbances [Maekawa et al., 2006; Yamauchi et al., 2007] and anomalous sporadic E layers were observed in prior to earthquakes [Sorokin et al., 2006a]; the effect was numerically modeled [Soloviev et al., 2006]. Various applications of Schumann resonance to ionospheric studies including an earthquake effect were reviewed [Nickolaenko and Hayakawa, 2007]. An electrodynamic model was developed for strong DC electric field formation in the ionosphere above earthquake regions [Sorokin et al., 2006].

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