

## **TIME-DOMAIN MATHEMATICAL MODEL OF IMPULSIVE EM NOISES EMITTED FROM DISCHARGES**

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**Abstract**—Impulsive electromagnetic (EM) noises emitted from discharges have been measured and characterized in ultra-wideband VHF channel. Statistical characteristics of EM pulses emitted from single discharge source are investigated as fundamental study. Firstly, the reproducibility of impulsive EM noises is confirmed by calculating their auto-correlations. The frequency spectrums of such pulses are found to be unique for each source. Next, statistical analysis is performed on the amplitude and inter-arrival time of received EM pulses. It is found that the probability distributions of amplitude and inter-arrival time of EM pulses follow normal and exponential distributions, respectively. Taking into account these ultra-wideband characteristics of impulsive EM noises from discharges, a mathematical model of EM pulses emitted from discharges is developed in the time domain. This is represented as a simple analytic formula with three parameters, which are derived from measurements. This model has been validated via measurement where multiple discharge sources exist.

## 1. INTRODUCTION

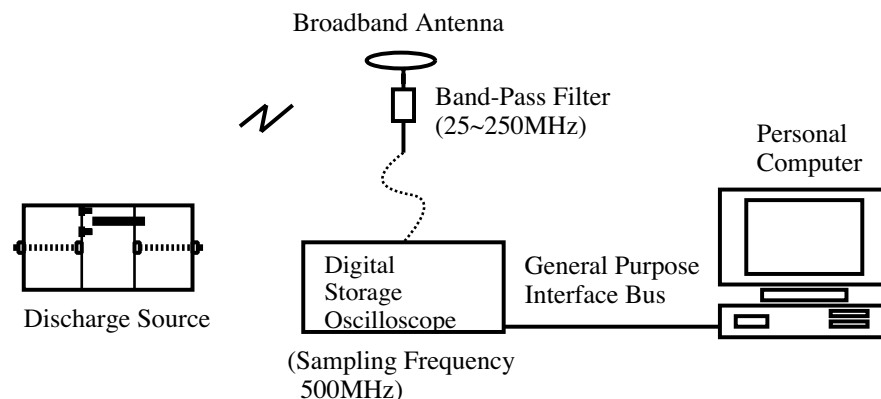
Until recently, investigation on electromagnetic (EM) noises has been conducted to establish wireless communication systems. Most sources, e.g., thermal and atmosphere noise, can be represented in terms of well-known Gaussian model. Impulsive EM noises that appear in urban environments are radiated from electrical self-starter of cars [1–4], fluorescent lights [5], photocopier machines [6], power apparatus, and so forth. Such noises are impulsive in nature and have larger amplitude than that of the Gaussian noise. It has been reported that impulsive noises degrade the quality of wireless communication systems and FM/television broadcasting [1–4, 6–9].

In the VHF region, discharges which are caused by the degradation of electric power apparatus, can be one of the dominant noise sources [10]. In industrial environments, such as factories, power plants, and so forth, the effect of impulsive EM noises on occupational communications cannot be neglected. Note that the frequency bands assigned for occupational communications systems are 80 MHz, 150 MHz, and 400 MHz in Japan, although they are different in each country. The point to be stressed here is that present communications systems have been developed without the influence of such noises taken into account. Thus, it is desirable to develop a mathematical model of impulsive EM noises for potential application to the development of future communications systems and system evaluation.

The objective of this paper is to examine ultra-wideband (UWB) characteristics of impulsive EM noises emitted from discharge sources. For this purpose, impulsive EM noises emitted from imitated electric discharges and electric power apparatus are received by a wideband antenna. Firstly, our attention is paid to the reproducibility of waveforms, since a mathematical model for impulsive noise can be developed easily if an adequate reproducibility is obtained. Then the amplitudes and inter-arrival times for the EM pulses are investigated for the determination of a noise model statistically. Based on these results, a mathematical model for impulsive noises is proposed and verified using measured data. For our preliminary work, refer to [11].

## 2. EXPERIMENTAL SETUP

Three discharge sources are considered in this paper. These sources are further classified into two classes. One is an imitated electric discharge; a needle-plane electrode is considered, and then a high voltage is applied (3 kV). The others are partial discharge sources of electric power apparatus. Two kinds of apparatus are considered; forced draft



**Figure 1.** Schematic explanation of experimental setup.

fans (FDF) and condensate booster pumps (CBP).

Schematic explanation of our measurement system is illustrated in Fig. 1. EM pulses emitted from a source are received through a wideband circular-plate antenna [12] which is located in front of an apparatus. The diameter of the circular plate is 30 cm. Note that circular plate antennas are commonly used for lightning observation because of relatively broadband characteristics and omni-directional radiation pattern on the horizontal plane. The return loss of this antenna is dependent on the frequency of EM pulses, but smaller than 3 dB at least from 25–150 MHz, which is dominant frequency band of EM noise emitted from discharges. The reason for choosing this antenna is attributed to limited space in a power plant. It should be noted that the amplitude of EM pulses can be calibrated using an antenna factor. However, calibration was not applied to the data obtained in our measurement, since the purpose of this paper is to investigate fundamental characteristics of EM pulses in UWB channel; (i) the reproducibility of EM pulse for each source, (ii) the dependency of frequency spectrum of EM pulses, and (iii) a parameterization of the amplitude distribution and inter-arrival time of EM pulses, if the reproducibility is confirmed. Namely, above-mentioned interests are not affected by the antenna characteristics. The received pulses are filtered by a band-pass filter (25–250 MHz). Then, A/D conversion is applied to the signals with a digital storage oscilloscope (8-bit). In this measurement, the sampling frequency is 500 MHz. A personal computer is used for data recording and control of our measurement. In order to detect pulse-train EM noises, the whole memory of the oscilloscope was divided into 500 segments. Each segment can record

an EM pulse for the time window of  $2.0\ \mu\text{sec}$ . This is because typical duration of EM pulses from discharges are hundreds of microseconds at most [10]. Signals whose amplitude exceeds a trigger level are recorded using the sequential trigger mode of the oscilloscope.

It is noteworthy that the density of power apparatus is high in power plants. In some cases, the separation between the apparatuses was 2.0 m at most. For acquitting EM pulses emitted from single source properly, the remaining apparatuses within 10 m were shutdown during the measurement. Figure 2 is a photograph of apparatuses in a power plant with the antenna.



**Figure 2.** Photograph of power apparatuses and the antenna in a power plant.

### 3. STATISTICAL ANALYSIS OF MEASURED DATA

#### 3.1. Reproducibility of EM Pulses

The reproducibility of waveforms is investigated since a mathematical model for impulsive noise can be developed easily if an adequate reproducibility is obtained. For example, the duration of EM pulses is determined uniquely. Received impulsive EM noises are analyzed statistically in order to investigate their reproducibility in the time domain. The maximum auto-correlation coefficient between an ensemble average of EM pulses and each EM pulse is used as a measure. Note that the ensemble-averaged waveform for a source is

calculated by averaging over all pulses emitted from each source. The auto-correlation is given by the following equation:

$$R(\tau) = \frac{C_{fg}(\tau)}{C_{ff}(0)C_{gg}(0)} \quad (1)$$

where

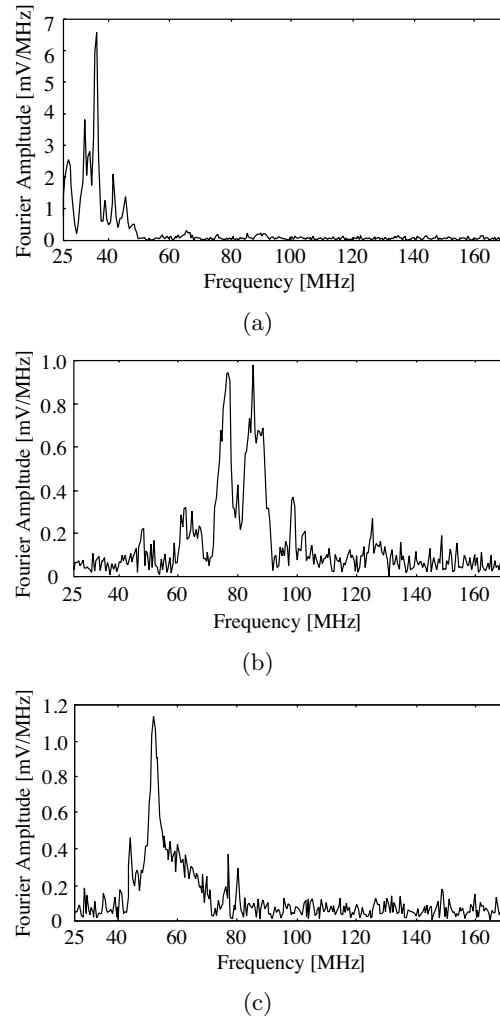
$$C_{ff}(0) = \sum_{t=1} f(t)^2 \quad (2)$$

$$C_{gg}(0) = \sum_{t=1} g(t)^2 \quad (3)$$

$$C_{fg}(\tau) = \sum_t f(t)g(t+\tau)dt. \quad (4)$$

where  $f$  and  $g$  express ensemble-averaged waveform and pulse emitted from the same source, and  $R$  denote an auto-correlation coefficient. This is evaluated in the time domain for fixed source-antenna distance, e.g., 1.2 m. The average value of the auto-correlation coefficient for EM pulses from a needle-plane electrode, FDF, and CBP were 0.988, 0.752, and 0.622, respectively. It should be noted that the latter two values are smaller than the former. This is attributed to the effect of back ground noise. Namely, noise sources, which not directly related to discharges, would exist even in power apparatuses. In addition, the latter amplitudes were relatively small (see Fig. 3). The auto-correlation coefficient for a needle-plane is evaluated for different fixed source-antenna distance of 2.4 m and 4.8 m. The averaged values were 0.971, and 0.966, respectively. From this discussion, the waveform reproducibility was confirmed for each source. Next, the auto-correlation is compared for EM pulses received at a different distance. The averaged value of the auto-correlation coefficient for EM pulses of 1.2 m and those of 2.4 m was 0.868. For the distances of 1.2 m and 4.8 m, the auto-correlation was 0.785. Namely, reasonable reproducibility is observed within 5 m at least. This region is in our main interest, since the EM power density emitted from the source, roughly speaking, varies inversely as the square of the distance from the source and high density of power apparatus. It should be noted that one of the main reasons for the decrease of auto-correlation is the reflection from the ground. When the correlations are calculated in the frequency domain, on the other hand, the auto-correlation was 0.951 for EM pulses emitted from 1.2 m versus 2.4 m, 0.913 for 1.2 m and 4.8 m, respectively. This is because an obvious change, such as occurrence of new frequency component, never happens due to the reflection from the ground. Thus, discussion in the frequency

domain could be more reasonable than that in the time domain when investigating fundamental characteristics. Figure 3 shows the Fourier spectrum of EM pulses emitted from (a) the needle-plane electrode, (b) FDF, and (c) CBP. As is evident from this figure, the frequency spectrums of EM pulses are unique for different sources.



**Figure 3.** Frequency spectrum of EM waves emitted from (a) electrode, (b) forced draft fan, and (c) condensate booster pump.

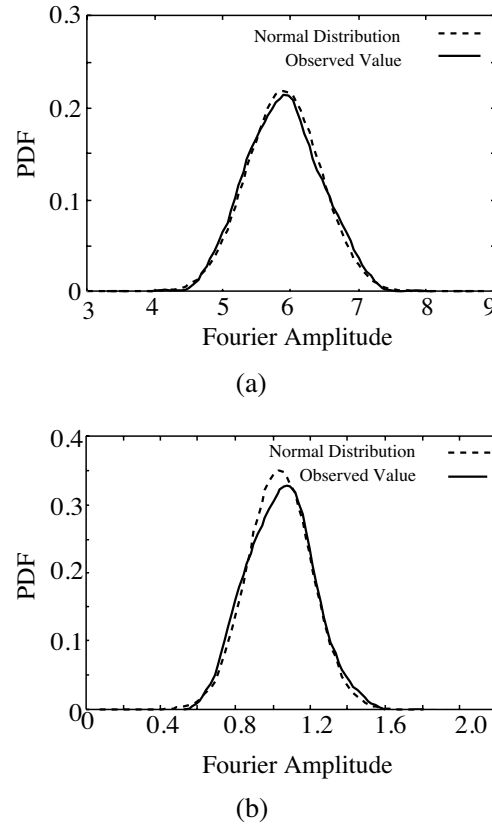
### 3.2. Amplitude Probability Distribution

Probability distribution of pulse amplitude is investigated in this subsection. In particular, we study the Fourier amplitude at the frequency where its amplitude becomes maxima. This is because peak amplitude in the time domain is more sensitive to background noise and quantization error than that in the frequency domain, as presented in Section 3.1. Figures 4(a) and (b) show the amplitude probability distribution functions (PDFs) for EM noises emitted from the needle-plane electrode and the FDF, respectively. The solid and dotted lines in the figures represent the observed values and the normal distribution in terms of average and variance values derived using the observed values. The distribution for the CBP is not shown, as that is similar to (b). From these figures, the amplitudes of EM pulses follow normal distributions. Note that the intensity of amplitude is different for each source, since the frequency we paid attention is different. The same investigation was conducted for another but the same-type FDF. It was found that the measured waveforms were almost identical. The average intensity at 89.2 MHz where Fourier amplitude takes maximum was 2.1 [mV/MHz] while was 5.9 [mV/MHz] in Fig. 4(a). This result implies that the intensity of the electromagnetic radiation would be different even for the same kind of apparatuses, which might be attributed to the degree of deterioration.

### 3.3. Probability Distribution of Inter-arrival Time

The inter-arrival time between pulses is defined as the time difference between the trigger times. Statistical analysis of the inter-arrival time is performed for each source. Figure 5 shows the relation between the inter-arrival time and the amplitude for the needle-plane electrode, FDF, and CBP. For needle-plane electrode and FDF, EM pulses are emitted at intervals of integral multiples of 60 and 120 Hz, respectively. It is noteworthy that the frequency of electricity in the power plant is 60 Hz. For the CBP, the EM pulses are emitted at random, and the inter-arrival time is much shorter than those of the other sources. The mechanism of pulse generation may be different. One possible reason is attributed to the dust piled on the surface of the electrical apparatus, resulting in a spark discharge. The EM pulses from other sources are generated by partial discharges in motors. The point to be stressed here is that no correlation exists between the amplitude and inter-arrival time of EM pulses for all sources considered in this paper.

Figure 6 shows the probability of inter-arrival time for the needle-plane electrode, FDF, and CBP respectively. The solid and dotted lines in the figures express the observed values and an exponential



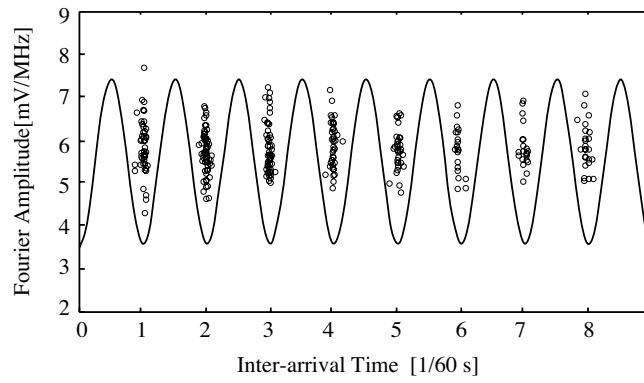
**Figure 4.** Probability distribution of amplitude: (a) electrode and (b) forced draft fan.

distribution in terms of average and variance values for measured data. It should be noted that the inter-arrival times follow exponential distributions. Thus the occurrence of EM pulses can be considered to follow continuous Poisson process for the EM pulses from CBP, while discrete one for the case of partial discharges as the interval is integral multiples of 60 or 120 Hz.

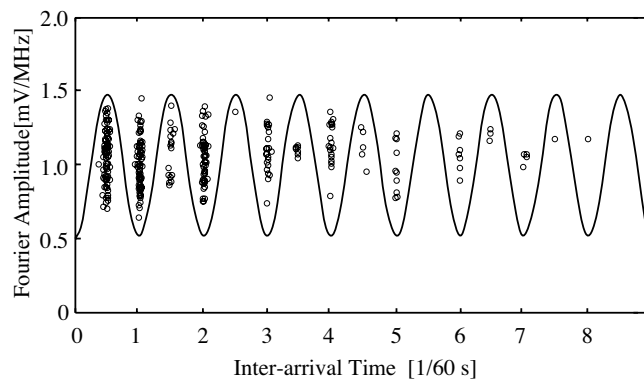
#### 4. DEVELOPMENT OF NOISE MODEL AND VALIDATION

Based on the results in Section 3, let us develop a noise model of EM pulses. The followings are the precondition validated in the Sections 3.1–3.3:

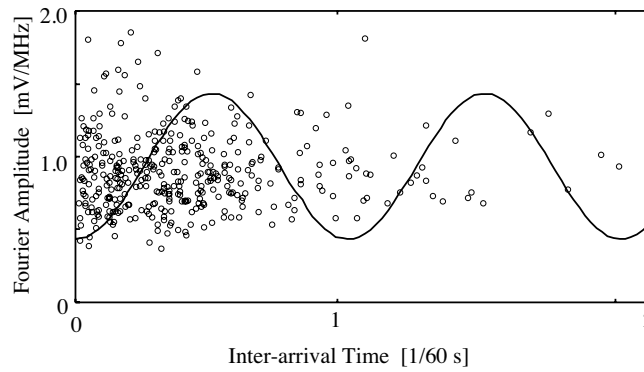




(a)

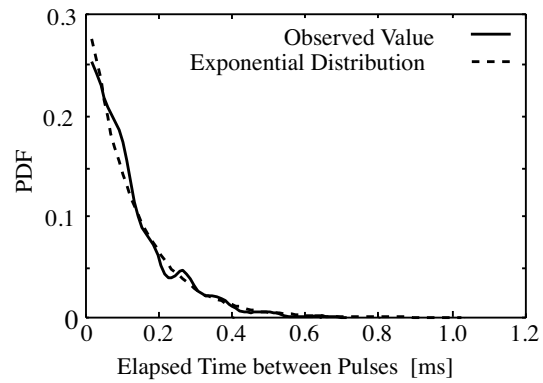


(b)

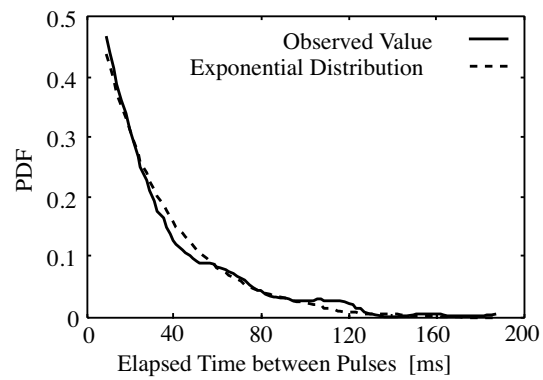


(c)

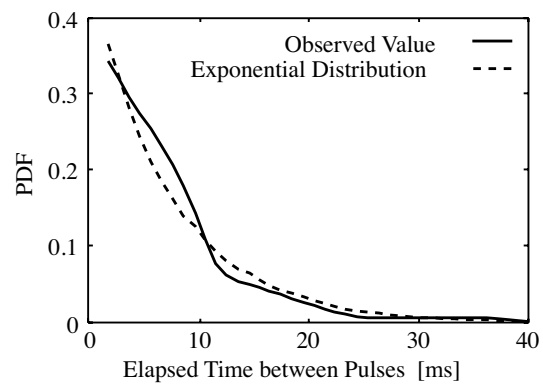
**Figure 5.** Relation between inter-arrival time and amplitude: (a) electrode, (b) forced draft fan and (c) condensate booster pump.



(a)



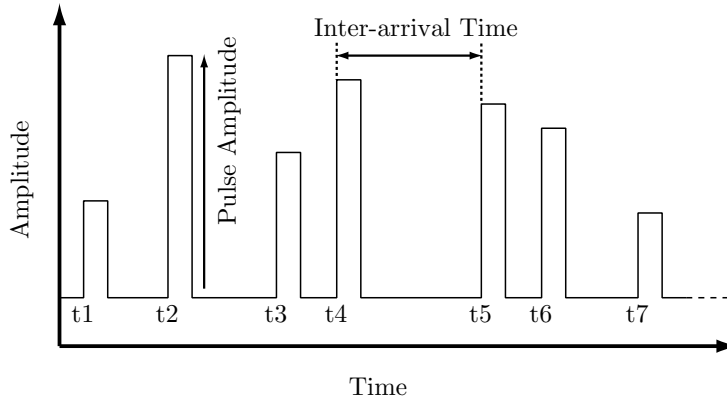
(b)



(c)

**Figure 6.** Probability distribution of inter-arrival time: (a) electrode, (b) forced draft fan and (c) condensate booster pump.

- Pulse durations of EM pulses emitted from each source can be considered as constant, which is supported by waveform reproducibility;
- Amplitude  $a_i$  for the EM pulses follows a normal distribution;
- Inter-arrival time of the EM pulses ( $t_i - t_{i-1}$ ) follow an (discrete) exponential distribution.



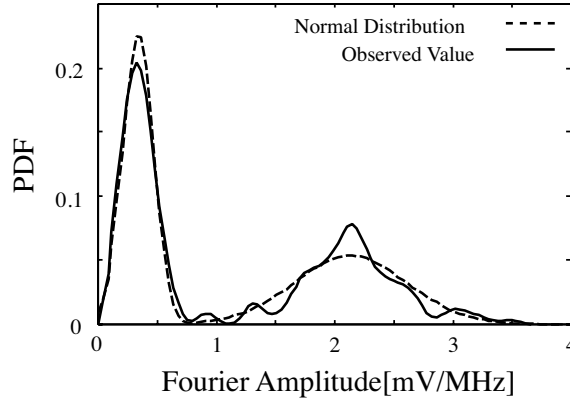
**Figure 7.** Conceptual view of noise model.

In Fig. 7, a schematic explanation of impulsive EM noises is illustrated. Impulsive EM noises in the time domain  $n(t)$  can be represented in terms of step function  $1_+$ :

$$n(t) = \sum_i a_i(t)(1_+(t - t_i) - 1_+(t - t_i + \Delta)) \quad (5)$$

where that  $t_i$ ,  $\Delta$  are the arrival time and pulse duration of EM pulses. During the time duration of  $\Delta$ ,  $a_i(t)$  is expressed using a unique waveform for each apparatus. Then, it takes zero between  $t_i + \Delta$  and  $t_{i+1}$ . According to this model, two random variables and one constant value is required to identify the characteristic of impulsive EM noise. Since EM pulses is considered emitted on the basis of the Poisson process, the model for an arbitrary number of sources can be represented as a simple summation of each EM pulses.

In order to validate the above mathematical model, we have measured a pulse-train emitted from a FDF. From this FDF, EM pulses were classified into two on the basis of the Fourier spectra. One was almost identical to Fig. 3(b), while that of the other is somewhat different. Among the total of 376 pulses, the numbers of the former and latter were 174 and 202, respectively. Figure 8 shows



**Figure 8.** Probability distribution of Fourier amplitude when two discharge sources exist. For EM pulses emitted from each source, measured values are fitted in terms of their average and variance values by assuming as a normal distribution.

the amplitude distribution at 50.8 MHz. As seen from this figure, the distribution seems a superposition of normal distributions. The dotted line represents the superposition of fitted normal distributions derived from average and variance for each waveform. Although we validated our mathematical model through an example of measurement, one of the pulses was dominant in most cases. The reason for this result is that inter-arrival times are largely dependent on each source, which is originated from the degree of deterioration of apparatus and nature of discharges as presented in Fig. 5.

## 5. DISCUSSION AND SUMMARY

This paper has attempted UWB modeling of EM noises emitted from discharge sources. First, we have investigated statistical characteristics of EM pulses emitted from single sources. The reproducibility of EM pulses was confirmed by calculating the auto correlation of EM pulses. One of the main results is that their frequency spectrums are dependent on discharge sources. Next, the statistical analysis was performed on the amplitude and inter-arrival time of received EM pulses. From this analysis, the probability distributions of the amplitude and inter-arrival time followed normal and exponential distributions, respectively. Taking into account these UWB characteristics of the impulsive EM noises, an EM noise model in the time domain was developed. The model was represented by a simple analytic formula

with three parameters that can be determined from measurements. This model was validated through measurements with two sources existed.

It is worth comparing our findings with those in previous papers. There are three main differences between them. Firstly, our attention was concentrated on EM noise emitted from discharge sources in electrical apparatus, while it was on electrical self-starter of cars [1–4], fluorescent lights [5], and photocopier machines [6]. Note that the mechanism of pulse emission would be different from each other. Especially, the inter-arrival time of self-starter of cars was reported to be dependent on engine speed [1]. The second difference is that single source was considered as a fundamental study for deriving a model, and then it was validated in practical situation. Note that measurements were conducted in practical situations only where unknown number of sources exists (e.g., [1–4]). In the previous paper, then, the amplitude and inter-arrival time of impulsive EM noises were concluded not to follow particular distributions in practical situations. The last difference is that UWB measurement has been conducted in this paper for clarifying the fundamental characteristics of EM noises. On the other hand, specific frequency bands are singled out in the previous papers. Through measurement at several frequency bands, no clear differences were observed for self-starter of the cars [4].

These findings could be informative when reviewing previous papers in this field.

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