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A New Optimized Localized Technique of CG Return Stroke Lightning Channel in Forest

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Abstract – Localization of lightning strike point (LSP) in the forest is modeled to mitigate the forest fire damage. Though forest fire ignited by lightning rarely happens, its damage on the forest is grievousness. Therefore, predicting accurate location of LSP becomes crucial in order to control the forest fire. In this paper, we proposed a new hybrid localization algorithm by combining the received signal strength (RSS) and the received signal strength ratio (RSSR) to improve the accuracy by mitigating the environmental effect of lightning strike location in the forest. The proposed hybrid algorithm employs antenna theory (AT) model of cloud-to-ground (CG) return stroke lightning channel to forecast the location of the lightning strike. The obtained results show that the proposed hybrid algorithm achieves better location accuracy compared to the existing RSS method for predicting the lightning strike location considering additive white Gaussian noise (AWGN) environment.

Keywords: Lightning, Localization, Antenna theory, RSSR, Sensor network.

1. Introduction

Forest is a prime facet of bionomical research. Forest fire extenuation has become a vital issue at the present time to minimize the mass ecological catastrophe. Thousands of square kilometers are cremated by forest fires with an immense amount of damage. More than 100 thousand forest fires occurred in the last decade in the whole world. The main cause of forest fire includes lightning, volcanic eruption, sparks from rock falls, and human activities. Though only one third of forest fires are enkindled by lightning, more than 85% of the total burned area is caused by lightning in Canada [1]. In Austria, 15% of forest fire is due to lightning and this figure rises to 40% during summer season [2].

Cloud-to-ground (CG) lightning is mainly responsible for forest fire. In nature, 90% of CG lightning is negative and the rest is positive. For the negative return stroke, peak current range, rate of change of the current range, and stroke duration are (4.6-80) kA, (5.5-32) kA/μs, and (30-200) μs, respectively. On the contrary, for the positive return stroke, peak current range, rate of change of the current range, and stroke duration are (4.6-250) kA, (5.5-32) kA/μs, and (25-2000) μs, respectively [3]. High temperature, which is generated by current and sufficient duration time of return stroke, is necessary to ignite woody fuels. Hence, the positive lightning is the prime candidate rather than negative lightning for setting off the forest fire [3]. To control lightning ignited forest fire, detection of igniting strike point in the forest (mainly positive lightning) is therefore essential [4]. Several techniques are studied to locate the lightning strike point (LSP). Most of the techniques are adopting time of arrival (TOA), time difference of arrival (TDOA), received signal strength (RSS) of receivers, and magnetic direction finder (MDF) [5-10].

Improving the location accuracy is the main challenge in localizing the lightning system to mitigate the forest fire effect. Cost and complexity of the algorithm are also vital issues for the localization. In TOA and TDOA techniques, time synchronization between global positioning systems (GPS) is required [11]. Nevertheless, it is complicated and costly [12]. In contrast, the RSS based localization is more straightforward and cost effective. In this study, the direct localization method is simulated first using the received electrical signal strength in a 2D environment. This position estimation is used as the boundary limits of genetic algorithm (GA) search space. The ratio of the received electrical signal of different couples of sensors is embedded in the fitness function of the GA. In this paper, the composite model of RSS and the received signal strength ratio (RSSR) is combined with the GA to estimate better localization accuracy of the LSP that will be compared with the RSS method.

The whole paper has been arranged in the following manner. Section 2 explains the propagation of lightning signal. In Section 3, we propose the hybrid localization algorithm of RSS and RSSR. In Section 4, we present the

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results analysis and performance evaluation. Finally, Section 5 provides the concluding remarks.

2. Lightning Signal Propagation

The CG lightning is a natural electrical spark, which is almost two or three kilometers in length. In this study, the CG return stroke lightning channel radiation propagation model is investigated for better representation of real life CG lightning strike. From the previous study, Bruce-Golde (BG) (equal current in whole return stoke channel), traveling current source (TCS), transmission line (TL), modified transmission line with linear current decay (MTLL), and modified transmission line with exponential current decay (MTLE) are developed to model the lightning return-stroke channel [13]. Those engineering models are grouped into two categories: the transmission line type models and traveling-current type models. The first category contains the TL, MTLL and MTLE models that are viewed as incorporating a current source at the channel as injecting a specified current wave which propagates upward into the channel without any distortion. In the traveling current type models, to which belongs the TCS and the BG models, the return current is viewed as being generated at the upward moving return stoke front and then propagating downward.

In the present decade, researchers have started to develop a new model based on antenna theory (AT). Researches proved that AT is one of the best models of electromagnetic radiation of CG return stroke lightning channel [14], [15]. The diameter of lightning channel is considered around 0.01 to 0.18 m [16]. Hence, lightning flash is a finite length of current carrying thin conductor, which radiates electromagnetic wave [17], [18].

The electromagnetic waves that are emitted from CG return stroke in forest propagate throughout the environment, are received by the sensors, as shown in Fig. 1.

Generally, the lightning current is higher in the channel closer to the ground. Therefore, the maximum field radiates from the lower section of lightning channel [18]. Hence, the effective part of the lightning channel can be treated as

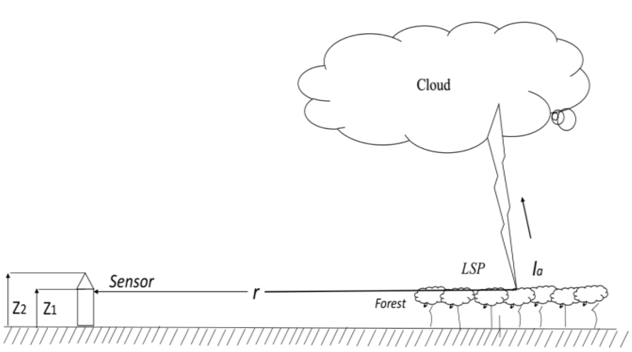

Fig. 1. Lightning strike in forest and measurement system of electromagnetic signal

a dipole antenna [19]. From the channel, three types of electromagnetic signal, namely, radioactive, inductive, and electrostatic are radiated. In the far field, the receiver only picks up the vertical polarized electrical signal [20]. The vertical polarized electric signal is given in (1) [19].

$$E_i = E_0 \left| \frac{Z_i - z_1}{\sqrt{r_i^2 + (Z_i - z_1)^2}} - \frac{Z_i - z_2}{\sqrt{r_i^2 + (Z_i - z_2)^2}} \right| \qquad (1)$$

where,

$$E_0 = \frac{I_a \mu_0 \omega}{4\pi}, r_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}, I_a = \max(I(z_1, t))$$

and

$$I(z_1, t) = \frac{I_0}{e^{-(\frac{\tau_1}{\tau_2})(\frac{n\tau_2}{\tau_1})^{(1/n)}}} \frac{(t/\tau_1)^n}{1 + (t/\tau_1)^n} e^{-t/\tau_2} \text{ [13].}$$

Here, E_0 is the peak electric signal strength of lightning channel, μ_0 is the permittivity of free space, ω is the angular velocity, E_i is the RSS at receiver, (x, y) is the unknown coordinate of the electromagnetic source of LSP, (x_i, y_i) is the known coordinate of the receivers, Z_i is the height of the receivers from the ground, z_1 is the height of the lower part of the source (LSP) from the ground, z_2 is the height of the upper part of the source (LSP) from the ground, r_i is the horizontal distance between the source and the receivers, i is the index of the receivers 1, 2, 3, 4, …, N, I_a is the pick channel based current, $I(z_1, t)$ is the standard channel based current of lightning return stroke, I_0 is the amplitude of the channel based current, τ_1 is the front time constant, τ_2 is the decay time constant and n is the exponent having the value of 2 to 10.

Most of the theoretical studies are dealing with the electromagnetic field radiation from lightning strikes to the forest, assuming the ground to be a perfectly-conducting (P-C) plane. However, there is experimental evidence that the finite ground conductivity affects the radiated electromagnetic fields [21]. More precisely, the propagation of lightning electromagnetic fields along the earth surface results in the attenuation of the radiated components of the field spectrum associated with the initial rise to the peak of the electric. The equation (1a) is obtained after considering the ground conductivity of σ.

$$E_{(r,t,\sigma)} = E_i S(r, t, \sigma) \qquad (1a)$$

where $S(r, t, \sigma) = 1 - e^{(-\frac{t^2 \mu_0 \sigma c^3}{2r_i})}$ is the attenuation function for the case of homogeneous ground [22].

Due to high amplitude of lightning radiated signals, the noise is considered based on additive white Gaussian noise

(AWGN) only [23]. Thus, the measurement field strength can be expressed as follows:

$$E_{mi} = [E_{m1}, E_{m2}, E_{m3}, ..., E_{mi}] = E_i + n \tag{2}$$

where $E_i = [E_1, E_2, ..., E_N]$ is the RSS of the receivers without environmental effect and $n(A_n, \sigma)$ is AWGN [24]. Here, σ is the variance and A_n is the mean amplitude of the AWGN noise.

3. Proposed Hybrid Localization Algorithm

In this section, we discuss the proposed hybrid localization algorithm of RSSR and RSS, which is based on AT of CG return strokes lightning channel, followed by GA.

The sensor and LSP geometry of RSS method is shown in Fig. 2, where minimum three sensors are needed to estimate the position of LSP. Three circles are created by the three sensors, which are intersected in one point and that point is the estimated position of LSP. In the RSSR method, minimum three sensors are also required. The received signal ratio of the two sensors is formed as a hyperbola, which has two focus points. Two hyperbolas are intersected in one point, which is the estimated position of LSP, as shown in Fig. 3.

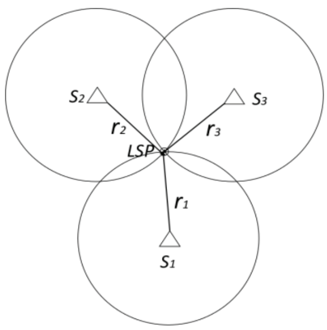

Fig. 2. Localization geometry of RSS method

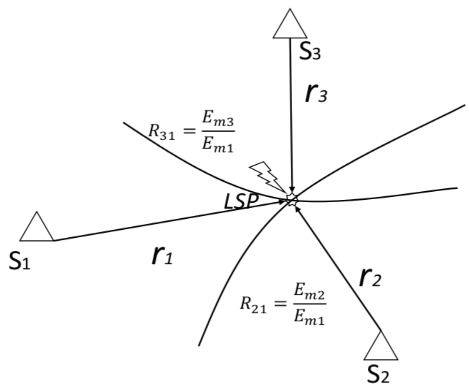

Fig. 3. Localization geometry of RSSR method

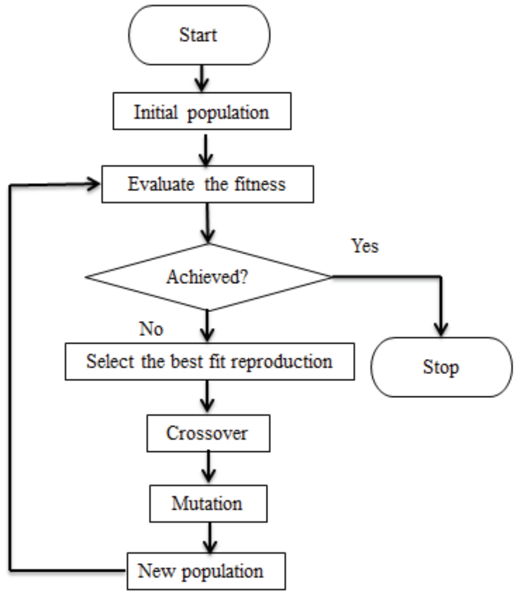

Fig. 4. Block diagram of simple GA

The equation of i-th sensor is obtained from (2) as follows:

$$E_{mi} = E_0 \left| \frac{Z_i - z_1}{\sqrt{r_{ei}^2 + (Z_i - z_1)^2}} - \frac{Z_i - z_2}{\sqrt{r_{ei}^2 + (Z_i - z_2)^2}} \right| \tag{3}$$

where $r_{ei} = r_i + \text{distance error for AWGN}$.

In RSSR method, one reference sensor is needed, which is denoted by S_1. The received signal strength ratio of i-th sensor with respect to reference sensor is,

$$R_{i1} = \frac{E_{mi}}{E_{m1}}, \text{ where } i \neq 1 \tag{4}$$

To estimate the optimum horizontal distances r_{e1}, r_{e2}, $r_{e3}, \ldots, r_{ei}$ between LSP and different sensors from (4), we use here GA that is a search heuristic, which mimics the process of natural evolution. This heuristic is routinely used to generate useful solutions to optimization and search problems. GA belongs to the larger class of evolutionary algorithms, which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection and crossover [25]. Hence, GA is one of the best methods to do the global optimization [25]. Thereby, we have applied the GA to find out the best approximation of auxiliary vector. A simple GA procedure has been presented in Fig. 4.

3.1 Initial population

A GA is a probabilistic system that has established the standards of genetics. In this system, the first style is to depict the length of the genetic string named Chromosome.

These Chromosomes having a quality of the destination role are termed as Chromosome's fitness. After selecting the length of Chromosome, the initial samples of the Chromosome relies on the arbitrary collection of a number of chromosomes.

In this suggested issue, to determine the values of the horizontal distance, GA is applied, which permitted maximizing the value of (4). GA is designed as follows: the construction of the Chromosome is 30 bits separated into i^{th} genes *G1, G2,…,Gi* presenting the horizontal distance of source and sensors. Those chromosomes are obtained by rearranging (3) as follows,

$$C_i = \frac{A_i}{\sqrt{r_{ei}^2 + A_i^2}} - \frac{F_i}{\sqrt{r_{ei}^2 + F_i^2}} \tag{5}$$

Squaring both left and right sides of (5) yields,

$$A_i^2 r_{ei}^2 + A_i^2 F_i^2 = (C_i^2 r_{ei}^2 + D_i + 2C_i F_i \sqrt{r_{ei}^2 + F_i^2})(r_{ei}^2 + A_i^2) \tag{6}$$

As $r_{ei}^2 >> F_i^2$, we can derive (6) as follows:

$$\begin{aligned} &C_i^2 r_{ei}^4 + 2C_i F_i r_{ei}^3 + r_{ei}^2 (D_i + C_i^2 A_i^2 - A_i^2) + \\ &2C_i F_i A_i^2 r_{ei} + (D_i + A_i^2 - A_i^2 F_i^2) = 0 \end{aligned} \tag{7}$$

where $A_i = Z_i - z_1, F_i = Z_i - z_2, C_i = \frac{E_{mi}}{E_0}, D_i = F_i^2 (C_i^2 + 1)$.

From (7), four roots can be derived. For the boundary condition of GA, it is very important to choose a correct root from those four roots. In the following way, the correct root can be found. If only one root is positive, then it can be used for the boundary condition of the GA. If all roots are positive, it selects one of which gives the almost theoretical value of $E_i(r)$ in (1). If all are negative or imaginary, then the absolute value of the real part is used for the boundary condition.

As an example, two binary strings of the Chromosomes are B1 and B2, where

B1= 1 0 1 1 0 1
B2= 0 1 1 0 1 0

Based on the fitness of individual population, a probabilistic choice is made at this stage. The program is stopped when the fitness value of any individual population reaches the expected value. Otherwise, it goes through the next step called crossover after selecting the best fit population.

3.2 Crossover

The genetic operator is utilized after the determination operation for generating new results depending on the current results in the sample. Two sorts of essential specialists can be found, one is a crossover and another is mutation. The input of the crossover operation is a couple of Chromosome called Guardians and the output gives a reproduced Chromosome known as Children. Sets associated with individuals were picked up arbitrarily from the mating pool according to the probability of crossover. Provided that the parallel letter set was utilized within GA then every spot was given transformation probability from 0 to 1. The variation in the quality is generally low.

The crossover is done in two steps for selected two Chromosomes: (1) the samples are represented by the binary strings and (2) according to the probability distribution, two Chromosomes do crossover in which binary strings can be switched. Therefore, single point crossover and two point crossover are used for these Chromosomes. By using uniform probability distribution, the crossover point is chosen. As an example, if 5 is the crossover site, the aforementioned B1 and B2 is changed after first step crossover and A1 and A2 will be

A1= 1 0 1 1 <u>1 0</u>
A2= 0 1 1 0 <u>0 1</u>

The sample uses the uniform crossover in the first step. In the step, binary strings are created and the common terms are searched in both parents, to find out the common mark in the common terms. In the string template, the binary bit will be set to 1 when there is matching term in both parents, otherwise, it will be zero. Again from the population, two numbers are selected randomly and exchanged with each other. As an example, if M1 and M2 are the sets of random number as

M1= 9 13 15 14 20 17 11
M2= 21 17 11 12 15 19 10 13 16

And, these M1 and M2 are made crossover with B1 and B2, the two parents Chromosomes are changed after the first step crossover. The new children will be like as

T1= 1 0 1 1 1 0 9 13 15 14 20 17 11
T2= 0 1 1 0 0 1 21 17 11 12 15 19 10 13 16

Second step crossover is done to increase the diversity and the new Chromosomes becomes

T1= 1 0 1 1 1 0 <u>21 17 11 12 15 19 10 13 16</u>
T2= 0 1 1 0 0 1 <u>9 13 15 14 20 17 11</u>

Within GA to reach the very least or perhaps the greatest position in search engine optimization, progress as well as procedure of selection is usually duplicated. When the fitness of the best Chromosome does not change significantly, the GA operation is completed.

3.3 Mutation

Changing a small number of bases randomly with small probability is known as mutation. It is performed for maintaining the diversity in the population. To avoid the parameter convergence, this operation is essential. The proper convergence of the GA is dependent upon its configuration, which is a very important issue. This convergence is made by defining the control parameters, like the population size, the Chromosome size, mutation rate and crossover point. Unfortunately, it is a very difficult task to determine these parameters and in most of the cases, they are defined empirically. From the population, each selected Chromosome was mutated separately, like crossover. The operator exchanges with a randomly selected term in the corresponding complimentary subset of the string. In this case, a simple point mutation is used. As an example, after mutation T1 will be as follows:

T1= 1 0 0 10 17 11 12 15 19 48 13 16

Parameters for the genetic algorithm configuration are:

- Size of the population: 700
- Rate of mutation: 0.35%
- Stopping criteria: 200

This whole process runs until reaching the best optimum value of the fitness function. The best population (best horizontal distance from the LSP to receivers) is obtained with respect to the best fitness value of the fitness function.

The obtained distance data vector from GA is,

$$D=[r_{e1}\ r_{e2}\ r_{e3} \dots r_{eN}]$$

And, the true distance vector is,

$$d=[r_1\ r_2\ r_3 \dots r_N]$$

Using the maximum likelihood (ML) estimation, (8) is obtained where $\theta = [x\ y]^T$.

$$In\ \mathcal{L}(\theta \mid r_{e1}\ r_{e2}\ r_{e3} \dots r_{eN}) = \prod_{i=1}^{N} PDF(r_{ei} \mid \theta) \tag{8}$$

where $\mathcal{L}$ is the likelihood function and PDF is the probability density function. After some steps, (9) is obtained from (8),

$$\theta = \arg\max\left(In\ \mathcal{L}(\theta \mid r_{e1}\ r_{e2}\ r_{e3} \dots r_{eN})\right) \tag{9}$$

From (9), we obtain the estimated position of the electromagnetic source. Let the actual coordinate of electromagnetic source be (X_a, Y_a) and the number of independent trials in the simulation is 2500, then we obtain the root mean square (RMS) error of lightning location accuracy (LLA) by using (10).

$$Error = \sqrt{\frac{\sum_{o}^{n}(x-X_a)^2+(y-Y_a)^2}{n}} \tag{10}$$

4. Results and Discussion

In this section, we represent the results analysis and performance comparison between the proposed method and the RSS method based on AT model of CG return stroke lightning channel. In this simulation, we assume the receiver with high pass filter for picking up 1 MHz center frequency of the electric field of lightning channel [3], 125 km baseline of the receivers and the average height of the forest is from 10 m to 13 m [26]. We have simulated the proposed model and the existing RSS model of lightning at various peak current (2-20) kA of lightning channel under AWGN. For simulation, MATLAB is used in core i7 processor with 8 GB RAM. The simulation procedure is given below:

1) First step:
   1.1 Select the initial value of horizontal distances between the LSP and receivers by using (7).
2) Second step:
   2.1 Initial values are used as the boundary condition of GA.
   2.2 Find out the best fit horizontal distances between the LSP and receivers from GA by using (4) as the fitness function of GA.
3) Third step:
   3.1 Apply the ML into the best fit horizontal distances, as shown in (9).
   3.2 Find out the estimated position of lightning strike.
4) Fourth step:
   4.1 Error calculation by following (10).

The obtained results are illustrated in Fig. 5 after completing all the steps of the simulation.

In Fig. 5, the simulated results are shown at peak current 2 kA, 10 kA, and 20 kA, respectively, and at a frequency of 1 MHz of lightning channel. For the first scenario, the obtained error of LLA are 2.765 km, 2.605 km, and 2.489 km for the RSS method and 1.305 km, 1.256 km, and

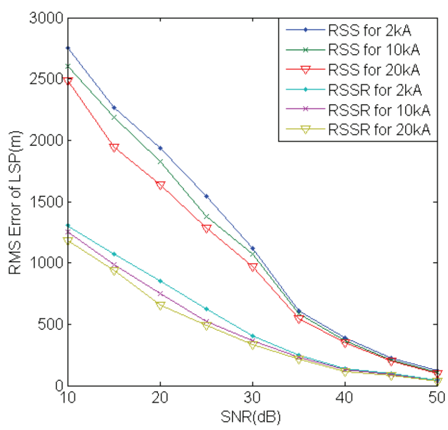

Fig. 5. RMS positioning error (m) of LSP with respect to SNR (dB) at peak current values of lightning channel 2 kA, 10 kA, and 20 kA, respectively

Table 1. RMS positioning error (m) of LSP with respect to different number of sensors at 30 dB noise

Method	Current (kA)	Number of Sensors			
		4	5	6	7
RSSR	20	201.47	110.56	65.89	40.1
	10	232.05	129.76	78.12	52.29
	2	245.12	162.43	99.78	77.46
RSS	20	523.51	260.79	251.63	140.25
	10	557.45	389.23	273.72	170.63
	2	630.89	510.33	305.73	225.5

1.185 km for the proposed method at peak current of lightning channel 2 kA, 10 kA, and 20 kA, respectively when the SNR is 10 dB. Next, the error of LLA becomes 1.120 km, 1.072 km, and 0.970 km for the RSS and 0.407 km, 0.3627 km, and 0.330 km for the proposed method when the SNR increases to 30 dB. Finally, the error of LLA are found to be 0.124 km, 0.108 km, and 0.097 km for the RSS and 0.0448 km, 0.0372 km, and 0.0331 km for the proposed method when the SNR is 50 dB at peak current 2 kA, 10 kA, and 20 kA, respectively.

The RMS position error comparison of LSP estimation for the proposed RSSR method and existing RSS method at 30 dB noise is represented in Table 1, where the numbers of sensors of network are varied. At 4 sensors, the error of LLA are observed 630.89 m, 557.45 m, and 523.51 m for the RSS method and 245.12 m, 232.05 m, and 201.47 m for the proposed method at peak current of lightning channel 2 kA, 10 kA, and 20 kA, respectively when the SNR is 30 dB. In addition, the error of LLA is reduced with the increment of network sensors due to the inconsistence reduction of non-linear equation.

The RMS comparison of LSP error (m) for the proposed method and RSS at noise 30 dB is represented in Table 2, where LSP is considered at the top of the forest and ground. Table 2 shows that, the RMS positioning error (m) of the LSP at ground is significantly greater than LSP at the top of the forest for the same pick channel based current. It is happening because the electrical signal strength of the LSP at ground is lower than the LSP at the tree.

The RMS comparison of LSP error (m) for the proposed method and RSS at noise 30 dB for different ground conductivity is represented in Table 3. The RMS error increases with decreasing ground conductivity. It is happening because of decreasing amplitude of the field and increasing its rise time with increasing propagation distance

Table 2. RMS positioning error (m) of LSP with respect to lightning strike at tree and ground for 30 dB noise

Method	Current (kA)	Lightning Strike	
		Tree	Tree
RSSR	20	201.47	201.47
	10	232.05	232.05
	2	245.12	245.12
RSS	20	523.51	523.51
	10	557.45	557.45
	2	630.89	630.89

Table 3. RMS positioning error (m) of LSP with respect to different ground conductivity for 30 dB noise

Method	Current (kA)	Ground Conductivity		
		P-C	0.01 S/m	0.001 S/m
RSSR	20	201.47	211.62	320.12
	10	232.05	247.63	372.43
	2	245.12	262.38	397.25
RSS	20	523.51	552.67	827.14
	10	557.45	607.82	886.89
	2	630.89	674.48	1000.32

Table 4. Recorded simulation time of the proposed method and RSS at 40 dB and 20 dB noise

Method	Current (kA)	Recorded Time (s)	
		40 dB	40 dB
RSSR	20	5.23	5.23
	10	6.15	6.15
	2	8.92	8.92
RSS	20	5.09	5.09
	10	5.98	5.98
	2	8.52	8.52

and/or decreasing ground conductivity. The equation (1a) is utilized for the replacement of (1) to estimate the ground conductivity effects for locating the LSP.

The recorded simulation time of the proposed method and RSS at noise 40 dB and 20 dB is represented in Table 4. The processing time of the proposed method is slightly greater than the RSS method due to little bit complex equation of the proposed method than that of the RSS. In addition, the simulation time is increased with the increment of noise because of high inconsistence data for high noise.

Finally, the proposed RSSR method to locate the position of the lightning is better than the existing RSS method, which is clearly justified in Fig. 5, Table 1 and Table 2 at low to high noise level and different sensors geometry. In practical field, the received field strength is increased with the increase of the peak current of CG lightning return stroke. For this reason, the noise effect of higher peak current signal is less than the low peak current signal. Therefore, the error of localization is less when the peak current is high. When the received signal is taken during a short period for analysis, the peak amplitude of the received signal must be greater than the peak value of theoretical received signal. After taking the ratio of practical received signal between two sensors, the noise effect must be mitigated, which is confirmed by our obtained results.

5. Conclusion

A hybrid model based on AT model of CG return stroke lightning channel in the central analyzer has been proposed in this paper. In this study, RSSR and RSS of receiver network are combinedly used for mitigating the noise effect in LLA. The proposed method is viable and achieves superior performance compared to the existing RSS technique. The proposed model can be easily implemented by changing the central analyzer program of the RSS based localization algorithm of CG return stroke lightning channel in the forest or other applications.

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