Paper

FDTD simulation and experimental result on VLF scattering by ionospheric perturbations in Earth-ionosphere waveguide

Non-member Takuya Otsuyama (The Univ. of Electro-Communications)
Member Masashi Hayakawa (The Univ. of Electro-Communications)

Amplitude and phase perturbations on subionospheric VLF signals (known as Trimpi effect) are thought to be due to the scattering of VLF waves by ionization perturbations caused by either the precipitation of higher energy electrons from the magnetosphere, lightning discharge or earthquakes. In this paper, we examine the VLF scattering by simulating the fast Trimpis due to the direct effect of lightning and we calculate amplitude and phase perturbations by such ionospheric perturbations using the conventional FDTD method. Finally, we compare our computational results with the data measured for Japanese sprite events, to estimate the validity of our modeling.

Keywords: FDTD, VLF scattering, Trimpis, Earth-ionosphere waveguide

1. Introduction

Perturbations in the lower ionosphere can be effectively monitored by the use of subionospheric VLF/LF propagation as the anomaly in its amplitude and phase, and these anomalies are called "Trimpis". The most popular one is the "classic Trimpi" (onset duration of 0.5 – 2.5 s and slow decay of a few tens of seconds), which is due to the precipitation of higher energy electrons into the lower ionosphere as the consequence of wave-particle interaction in the magnetosphere (1). Then, the second type of Trimpi is early Trimpi, or "early/fast Trimpi(with rapid onset and rapid decay of the order of a few hundred ms)" (1), which is due to a direct interaction of the lightning discharge with the ionosphere. In addition to these lightning-associated Trimpis, Hayakawa et al. have found the similar kind of ionospheric perturbations possibly associated with earthquakes (2), and, in this case, the perturbation seems to be much stronger in density change, much larger spatial scale and much longer time scale(of the order of days).

Numerical modelings on space Trimpis have been proposed by several authors. Poulsen et al. adopted a linear scattering (Born) approximation (3), in which intermode coupling is assumed to be negligible. Nunn has proposed 3D Born modeling in which he has taken into account the modal coupling (4). On the other hand, Baba and Hayakawa have proposed the exact solution for this scattering problem (non-Born approximation) by means of finite-element-method(FEM), of course with including the modal interaction, though their code is 2D (5) (6). Baba et al. and Nunn et al. compared those methods (7) (8). Recently, Soloviev and Agapov have developed a 3D analytical-numerical approach(non-Born case) (9).

The observed results on classic Trimpis are compared with the numerical modeling by the use of FDTD(finite-difference time-domain), in order to deduce the perturbation characteristics (10). Several papers have been published to deduce the characteristics of perturbed region by means of the comparison of the observed data to the simulations, but they are all for the study of classic Trimpis. This paper deals with the modeling of fast Trimpis (considerably different from classic Trimpis), by means of the FDTD method, and its comparison with experimental data.

2. Ionospheric models for simulating fast Trimpis

Fig. 1 illustrates the ionospheric model, in which an exponential conductivity profile is assumed and also we assume a perfectly conducting ground. This conductivity is calculated from the following equation,

$$\sigma = \sigma_i + \frac{e^2}{m_e}\frac{N_e}{\nu_e} \cdots\cdots\cdots\cdots (1)$$

where the first term on the right-hand side corresponds to ion conductivity which depends on height, and the second term refers to the conductivity due to electrons. The electron density is given by the following typical nighttime profile (5),

$$N_e(z) = 30.74\exp\{0.24(z-87)\} \cdots\cdots (2)$$

where N_e is given in cm^{-3}, and z is height from the ground in km. And the electron collision frequency used in Eq.(1) is given as follows:

$$\nu_e(z) = 5 \times 10^6 \exp\{-0.15(z-70)\} \cdots\cdots (3)$$

where ν_e is given in sec^{-1}. The bottom panel of Fig. 1 illustrates the conductivity profile for the modeling the ionospheric perturbation in the next section.

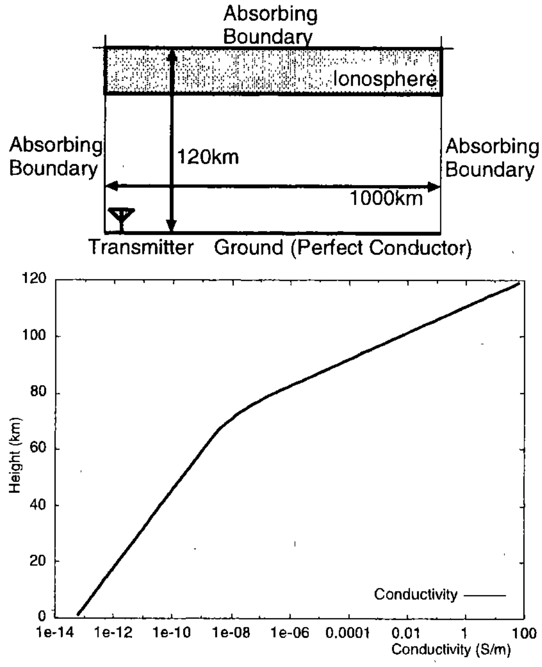

Fig. 1. The ionospheric model and conductivity profile.

3. Modeling the ionospheric perturbations for fast Trimpis due to a direct lightning effect

We have been trying to observe the mesospheric discharges(like sprites) mainly due to positive cloud-ground (CG) discharge and elves due to large CG discharges in Japan Sea side (so-called Hokuriku area) (11). Also we have been observing Trimpis at Kasugai and Maizuru (and some other stations in Japan) by using VLF and LF transmitters (12), but we deal with the LF(40kHz) transmitter located in Fukushima prefecture because we will use this LF subionospheric signal for the detection of fast Trimpis. We assume a plasma column (probably due to sprites) (13) with density perturbation $\Delta Ne = 10^4 cm^{-3}$ and vertical length=10-20km as in Fig. 2. These parameters are used to simulate the sprite-induced plasma column, but our 2D treatment in this paper makes the plasma column to be a plasma sheet. The column diameter is assumed to be 40km. The plasma column is located at 500 km away from the transmitter, and we will estimate the electromagnetic fields at various distances from the transmitter(Rx = 0 – 1000 km). The orthogonal coordinate system used is that z is directed upwards into the ionosphere and the (x,z) plane is the plane of propagation. It is a two-dimensional model in which invariance along the y-axis, i.e. in the direction perpendicular to the transmitter-receiver, is assumed$(\partial/\partial y = 0)$. We impose the electric field, $Ez = \sin(2\pi f \Delta tn)$ (f=40 kHz) at the origin(i.e. transmitter) as the source incident signal and we estimate the corresponding Ez at different x values. The grid size of the analyzing region should be smaller than one tenth of a wavelength, and so we adopted 500 m as the grid size. Except at the perfectly conducting ground, we used the absorption boundary of Mur's first order.Based on these conditions, we have computed three field components(Ex, Ez, and Hy).

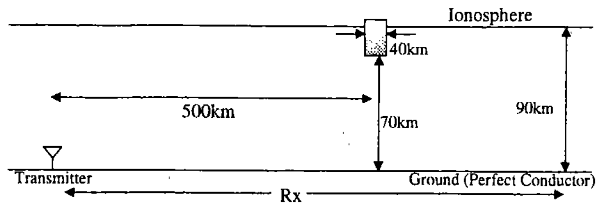

Fig. 2. The ionospheric model and sprite-associated ionospheric perturbation.

Fig. 3 shows the dependence of vertical electric field (Ez) intensity as a function of distance from the transmitter. The perturbation is centered at 500km, while the width of the perturbation is changed from 5 to 50km. The full line refers to the unperturbed situation, while other lines correspond to the situations with different plasma widths. This treatment is 2D, so that plasma column can be considered as a plasma sheet, being considerably different from reality. Fig 3 suggests that the minimums in the interference pattern of distance dependence of Ez are dependent on the plasma width, but the general behaviors(the distance dependence) is generally maintained. The field pattern in the upstream of the perturbation in Fig. 3 suggests that backscattering effect is negligibly small, but we can notice significant differences in the distance dependence in the downstream of the perturbation. That is, we expect an enhanced forward scattering, leading to the formation of an additional minimum probably because of the mode coupling and mode conversion at the perturbation.

Then, Fig. 4 illustrates the electric field intensity (Ez) versus distance, when the position of the perturbation is altered from 400 to 600 km away from the transmitter(with the plasma width being fixed to 20km). The full line again refers to the unperturbed situation, and

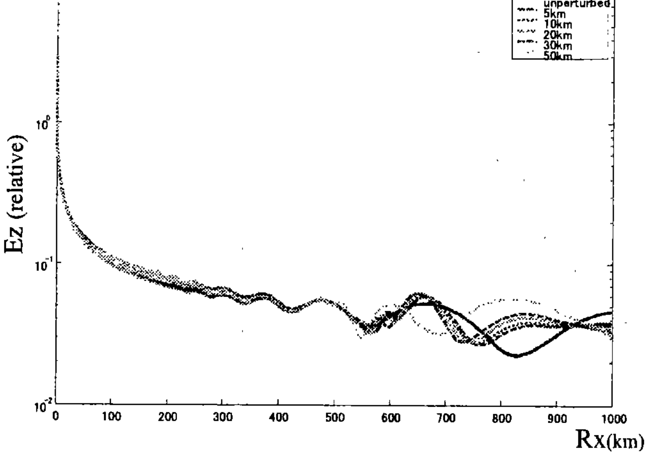

Fig. 3. Amplitude of vertical electric field (Ez) as a function of distance (Rx) for different widths of the ionospheric perturbation.

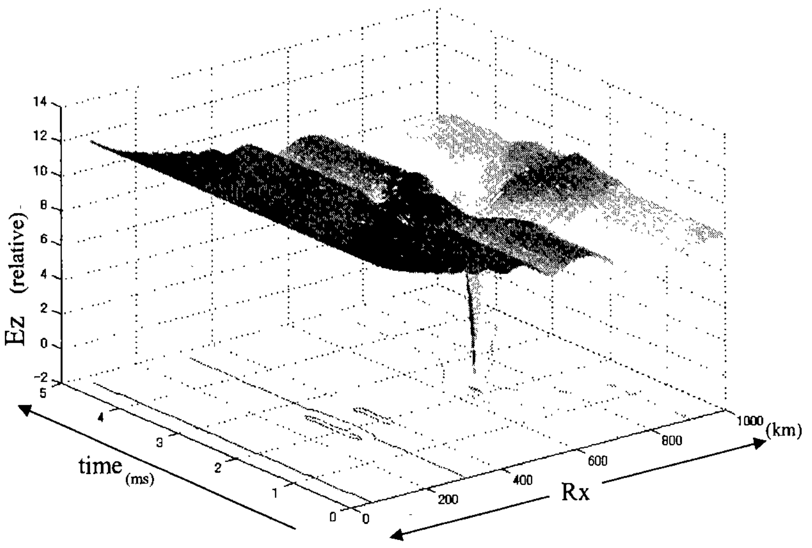

Fig. 6. The 3D plot of the electric field (Ez) intensity as functions of time and position. This figure is plotted except around the transmitter.

others to the perturbed situations with different positions of the ionospheric perturbation. At a fixed observer(downstream of the path), we can find out a lot of differences in intensity when the perturbation region is moved. As the result of comparison between Figs. 3 and 4, we can infer that electric field (Ez) changes at a particular observing point can be used to infer the position of the perturbation.

Next simulation is intended to be applied to the ionospheric perturbations due to elves (14). Elve-associated ionospheric perturbation is considered to be a direct coupling of lightning electromagnetic pulses (EMP) with the ionosphere and the perturbed region extends radially with the speed of light. Fig. 5 illustrates the model of elve-associated ionospheric perturbation. Its center is located at 500 km away from the transmitter, and the perturbation originates at the center and it will expand outward (radially) for 1.5 msec (that is, radius, up to 450km) and then the decay of ionization perturbation starts at the center and expands radially with the speed of light for 1.5 msec. Therefore, the duration of this perturbation at a particular position is 1.5 msec, and this model seems to be acceptable because the atmospheric relaxation time at this height is almost the same as 1.5 msec. The density perturbation is again assumed to be $5 \times 10^3 cm^{-3}$ and exists in the height range from the ionospheric bottom (h = 90 km) down to 80 km. Figs. 6 and 7 are the numerical results by FDTD. Fig. 6 shows the 3D plot of the electric field intensity as functions of time and position, in which the left oblique axis indicates the time elapsed and the right oblique axis, the distances from the transmitter. Fig. 7 shows the corresponding temporal evolution of Ez at a few fixed observer distances (300, 400, 500, 600 and 700

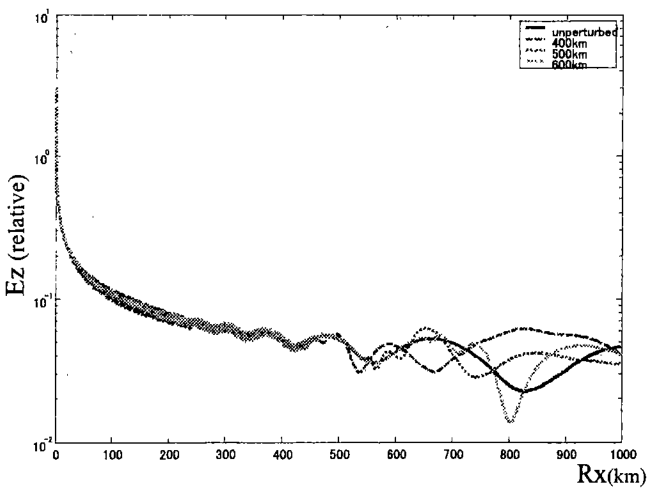

Fig. 4. Amplitude of vertical electric field (Ez) as a function of distance (Rx) for different positions of the ionospheric perturbation.

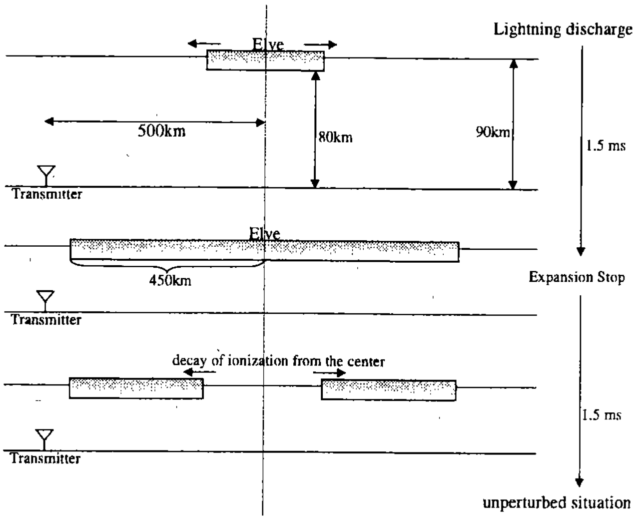

Fig. 5. The elve-associated ionospheric perturbation model.

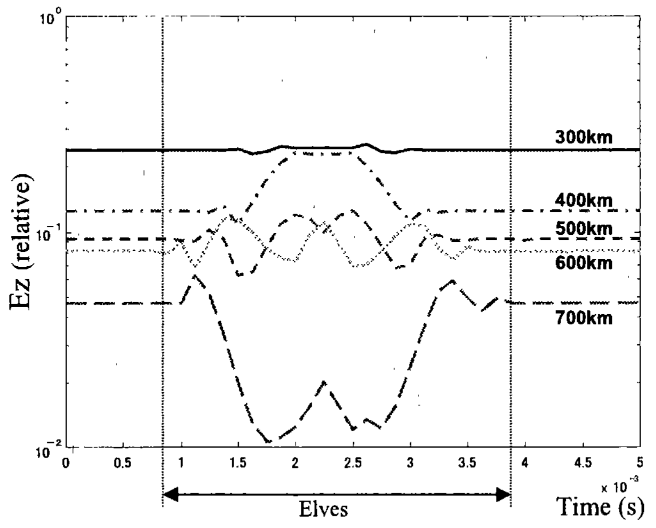

Fig. 7. The temporal evolution of Ez at several fixed observer distances.

km).

The following points have emerged from these two figures. (1)Near the center of an expanding perturbation (Rx $\sim$ 500km), there is observed small changes in Ez. (2)At the farther distance (Rx = 700 km), we find out very significant changes in Ez in Fig. 7. This is because this position corresponds to the interference minimum in Fig. 3, so that we expect a lof of changes in Ez at this distance. (3) A significant change in Ez is noticed in Figs. 6 and 7 at the distances of 250 to 400 km, and this is due to the scattering of the moving perturbation mainly in the upstream of the path. (4) Electric field changes are almost symmetric with respect to t = 2.3 ms when the ionospheric perturbation expands outward and when the perturbation returns to the unperturbed situation. (5) VLF scattering by elves looks to be considerably larger than that for sprites.

4. Comparison of our computational results with observed data

The first red sprites and elves were observed in Japan during the winter of 1998/99 in Hokuriku region by the group of Tohoku Univ. For these optical phenomena, detailed analysis such as ELF transients and VLF subionospheric disturbances was performed by Hobara et al.(11). Although VLF subionospheric disturbances occurred on VLF signals from the transmitter NWC from Australia, we compared our calculated results with the observed data. Kasugai (abbreviated KSG in Fig. 8) station is located in the upstream of the occurrence area of sprites and elves and all scattered signals at KSG are received as backscattered signal. Propagation distance between NWC transmitter and sprites/elves events area is about 6000 km, and the distance between NWC and Kasugai station is about 5800 km. The propagation path of NWC and JJY signals in Fukushima prefecture, sprites occurrence area and Kasugai station are shown in Figure 8.

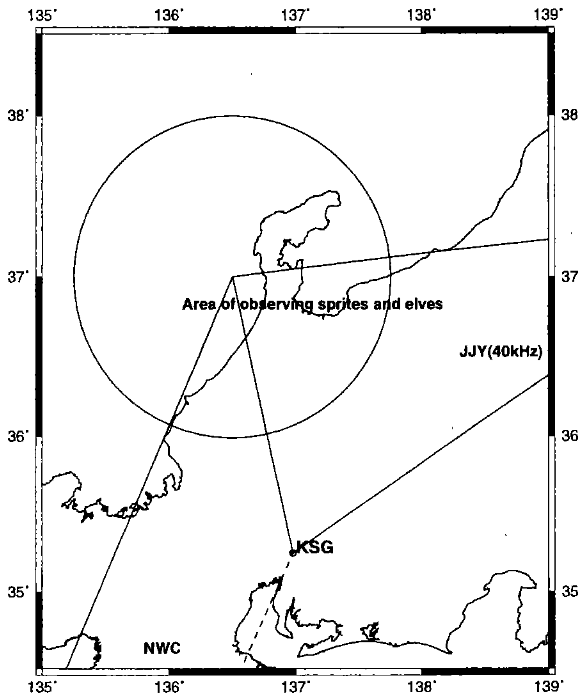

Fig. 8. The locations of optical events. VLF/LF great circle paths to Kasugai(KSG) and the area of sprites/elves events are also shown.

First of all, we have compared the computed results with the observation for the case of elves. Elves are known to have a large ionization region of the order of 150-300 km and also the distance between Kasugai and the optical region is only 200 km. So that, it may be reasonable to consider that the VLF receiver at KSG is located beneath the perturbed ionospheric region. Our calculation for elve-type ionospheric perturbations indicates that the intensity of scattered signal in the upstream of the ionization center is smaller than that in the downstream, but it may be possible to detect it. The results computed in the previous section indicate that at 200 km upstream of the center of ionospheric perturbation the peak intensity of scattered signal is about $-15dB$ relative to the direct signal. Though the location of elves was different from one event to another, correspondingly the different propagation length, the mean value of the observed scattered signal intensity would give us an insight of the general intensity. As shown in Table 1, this mean value of scattered signal is $-12.1dB$ (relative to the direct signal). Another thing we have to comment here is that the sampling of VLF observation system is 100 ms (much larger than the duration of elves($\sim$ 2 ms)), so that we are afraid that the receiver could respond to the elve properly. Even if we take into account these factors, it is generally considered that the computations are rather consistent with the observation.

Next the case of sprites is discussed. It seems that there is a discrepancy concerning the VLF scattering by sprites. Dowden et al.(13) concluded that the amplitude of backscattered signal associated with sprites is extremely strong, and they argued that sprite body

Table 1. Comparison between observed and calculated signal intensity relative to direct signal.

	Elves	Sprites
observation(mean value)	-12.1dB	-7.5dB
computation	-15dB	-30dB

is an extremely conducting column whose width is a few kilometers. However, the intensity of backscattered signal in our computations for the plasma column simulating the sprite is found to be very small, of the order of $-30dB$ relative to the direct signal. Previous other calculations using the Born (4) or non-Born (9) approximations and FEM (finite elements method) (6)(7) have yielded that the intensity of backscattered signal is generally relatively weak, though it increases with the increase its width. When the width is of the order of ~ 50 km, the backscattered signal intensity is about $-30dB$. These computational results are consistent with the results in this paper. However, the observed VLF scattering intensity for sprites was extremely strong with its mean value of $\sim -7.5dB$ in Hobara et al. (11). It is clear that our computational results are inconsistent with the result by Hobara et al. (11). We will consider the possible reason of this discrepancy between the computations including our present calculations and the observations by Dowden et al. (13), and Hobara et al. (11). In order to induce significantly strong scattering, the region of perturbation must be large enough, of the order of 100-200 km (total area) or even more. Hence, even though the optical measurements have detected only the most intense region of the order of ~ 40 km(total area), the weaker perturbed regions might be present, the total area being much larger than ~ 40km.

5. Conclusion

The purpose of this paper was to study the scattering characteristics of subionospheric VLF waves by the ionospheric perturbations due to the nearby lightning discharges. Two types of fast Trimpi phenomena are considered;(1) sprites(mesospheric optical emissions) and (2) elves (direct effect of lightning electromagnetic pulses(EMP)), and the corresponding ionospheric perturbations due to those two types are modeled. We have performed 2D simulations on the VLF scattering by those perturbed ionospheric models by means of FDTD method, and compared these computational results with the observations. As the results, it is found that our computed results for elve-associated ionospheric perturbations are generally consistent with the observation (11)(13). However, the computational results for sprite-associated perturbation have yielded extremely weak backscattering in the observation, which we expected an enhanced scattering. This discrepancy was discussed.

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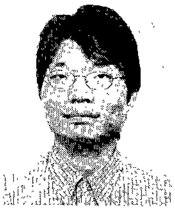

Takuya Otsuyama (Non-member) obtained Bachelor degree, Master degree from University of Electro-Communications in 1996 and 1998, respectively , and is presently Doctor course student at Univ. of Electro-Comms. He has been working on upper atmosphere discharge and Trimpi phenomena.

Masashi Hayakawa (Member) obtained Bachelor degree, Master degree from Nagoya University in 1966 and 1968, respectively. Doctor of Engineering from the same university in 1974. In 1970 he joined Research Institute of Atmospherics of Nagoya University as a Research Associate, and become Assistant and Associate Professors there. Since 1991 he has been a professor in University of Electro-Communications and has been working on space physics, atmospheric electricity, seismo-electromagnetics, EMC, inversion problem. IEICE, AGU, URSI member