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FOCUSING OF COSMIC RADIATION NEAR POWER LINES

- A THEORETICAL APPROACH

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Abstract- The purpose of this work is to determine if, and to what extent, cosmic radiation can be focused by power lines. As an alternative to experimental measurements, a computer program has been made to simulate particle trajectories. Starting from given initial values, the cosmic particles' trajectories through the electromagnetic field surrounding power lines are simulated. Particular efforts have been made to choose initial values which represent the actual physical condition of the cosmic radiation at ground level. The results show an average decrease in the particle flux density in an area below a power line and a corresponding increased flux between 12 m and 45 m on either side of the centre of the power line. The average shift in flux density is, however, extremely small (less than 0.1%) and probably not measurable with existing detector technology.

KEY WORDS:

Power lines; electromagnetic fields; cosmic radiation; focusing; particles; trajectory simulations;

INTRODUCTION

The debate concerning the possible health effects of residing close to high-tension power lines has not yet reached a final conclusion. There is still a frustrating lack of established connections between weak low frequency electromagnetic fields and biological response. Rather than solving this problem Anthony Hopwood has suggested a way to avoid it by introducing an alternative explanation to the reported increase in childhood cancer (Hopwood 1992). Based on experimental measurements with a GM-counter he put forward a hypothesis that explains biological effects from increased doses of ionising cosmic radiation and not from the electromagnetic field itself. Referring to interference from the earth's magnetic fields with low energy particles, observable as aurora in polar regions, he suggests that cosmic particles are deflected by the electromagnetic field surrounding the power lines. The overall result of the deflection was hypothesized as increased particle exposure on either side of the power lines.

Hopwood's hypothesis could be tested in two ways, either by more measurements or by theory. Both kinds of tests have been performed, and experimental studies have been carried out in several places in the world. The Swedish radiation protection authorities took some measurements (Lars Erik Paulsson, personal communication), but could not verify Hopwood's findings. Also, The National Radiation Protection Board in England has repeated the experiments and found no effects (Burgess and Clark 1994). They conducted their experiments in collaboration with Hopwood, but even so, the result was negative. In both the Swedish and British studies, measurements were performed at low altitude so that ionising radiation from the ground contributed considerably to the measurements. In the British study there may be an indication of a focusing effect, but only roughly at a 1% level, and far too small to be statistically significant.

In 1996 another experimental work was presented (Martinson et al. 1996). The authors used thermoluminiscence detectors which are not affected by magnetic fields. They also used a smart design where they took measurements on two different days, one with the line energised and one de-energised. Unfortunately, their description of what they mean by de-energised is not sufficient, since it is not clear whether the line had full electric potential (voltage) even if the current was very much reduced. The authors seem to be concerned with the magnetic field alone, while theoretical calculations indicate that it is the electrical field that is most important for the deflection of particles. Whatever voltage was applied to the de-energised line, Martinson and his co-workers could not pinpoint any "focusing effect" of the order claimed by Hopwood. However, the spread in the data is considerable and depends on the position along the ground, so a focusing effect of the order of a few percent would be impossible to detect using their experimental method.

Thermoluminiscent detectors were also used in an experiment where the detectors were left for up to three months to increase the precision of the measurements (Vistnes et al. 1997). Detectors were placed on the frozen surface of a mountain lake in order to increase the cosmic radiation (increases with the elevation) and to screen the detectors effectively from terrestrial radiation. However, even in that case no focusing effect could be demonstrated, which implies that the focusing effect seems only to yield maximally an increase of a few percent in the local cosmic radiation.

Theoretical studies have also been performed. Crude theoretical estimates do not seem to indicate any focusing effect, and several investigators have claimed that there cannot be any effect at all since the electric and magnetic fields vary sinusoidally such that the average effect must be zero. We have previously carried out a relatively detailed theoretical study based on calculations of individual particle trajectories through the electric and magnetic field close to a power line (Vistnes 1993). In that study we found that a focusing effect in principle could be expected, since the fields close to power lines can deflect some particles so that they hit the ground outside the area beneath the power line, while the opposite never takes place. However, the study showed that only low energy particles will be deflected, and, as well known, low energy particles have a short range in air. Thus, a final result could only be reliable if a more thorough analysis was performed. Such an analysis should cover all parameters, such as the number of various particle types, particle energy and direction in space and the range of the various particles in a statistically reliable way.

The aim of the present study was to carry out a theoretical analysis where all the relevant parameters are treated as completely as possible. A literature search was performed, and a computer program was developed for the purpose of simulating particle trajectories through the electromagnetic field. The program should use initial values with a statistical distribution that reflects the real physical condition. The results from the simulations could then be evaluated for changes in flux densities at ground level.

MATERIALS AND METHOD

Cosmic particles at ground level

The results to be presented in this research paper are based on a computer simulation program. Starting from given initial values, the program calculates particle trajectories through an inhomogeneous electromagnetic field. The accuracy of the results depends to a large extent on the choice of representative initial values. In order to make qualified choices, detailed information about the cosmic radiation at ground level is required. Of most interest is the absolute particle flux, the relative flux of different particle types and their respective velocity distributions. Some background knowledge of the cosmic radiation is required to understand the selections made for the simulations and the basis for the conclusions. A brief description is therefore given below. The information has been extracted from *Cosmical Geophysics* by Egeland, Holter and Omholdt (1973) and *Cosmic rays on earth* by Alkofer and Greider (1984). The interested reader is referred to the first book for an overview and to the last one for details.

The upper earth atmosphere is hit by a continues flow of *primary cosmic radiation.* Due to the earth's magnetic field, these particles have to exceed a certain *threshold energy* to reach the surface of the earth. The threshold energy depends upon the direction of the inbound particles and geographic latitude. It is common to separate the primary radiation into two parts. The isotropic *galactic radiation* consists of about 87% protons, 11% α-particles, 1 % electrons and 1% heavy nuclei. The dominating energy range is from 10^8 to 10^{11} eV. *Solar radiation* varies extensively in both particle type and energy with the 11-year activity cycle of the sun. Since the energy of these particles seldom exceeds 10^8 eV they are not a major contributor to cosmic radiation at sea level. The exception is areas of high magnetic latitude (polar regions) where the threshold energy approaches zero.

The cosmic particles that reach the surface of the earth are mainly secondary or higher order products of nuclear collisions between galactic radiation and atmospheric particles. Electrons are a special case since they are produced continuously by photon/electron cascades down through the atmosphere. This explains their high relative abundance, even though their range is short. At sea level, the overall result is a cosmic radiation flux of $2.4 \cdot 10^{-2}$ $cm^{-2}s^{-1}$. The major component is muons (63% of the total flux) followed by neutrons (21%), electrons (15%) and protons (0.6%). Antiparticles constitute a considerable part of the flux. They are, however, not treated separately in this paper since averaging over a whole phase period of the electromagnetic field (see below) renders the results independent of the sign of the elementary charge.

The differential energy spectrum $D(T)$ of each particle type may in general be described by an expression of the form: $D(T) = kT^{-\delta}$, where T is the kinetic energy of the particle and δ and k are parameters taken to be constant for a specified energy range. The particle-intensity dependence on zenith angle θ may be described by: $I(\theta) = I_v \cos^n \theta$, where I_v is the vertical intensity and n is a parameter, again constant for a specified energy range. The azimuthal intensity distribution is unprecisely taken to be isotropic. An azimuth (φ) dependent distribution function should give a slight east-west effect, caused by a combination of unequal numbers of particles and antiparticles, and their opposite deflection in the earth's magnetic field.

The parameter values are in general well known for high energy muons, but unfortunately burdened with much more uncertainty so far as low energy electrons are concerned. Precise parameter values for azimuth dependency are rare, but the existing ones indicate that the isotropy approximation is good.

For reasons described below, the simulation results presented in this paper are those for electrons. Values of the parameters used are: $\delta = 1.2$ for $T<100$ MeV, $\delta = 2.0$ for $T>100$ MeV, $n=2.0$ for $T<35$ MeV and $n=2.8$ for $T>35$ MeV. The values are given for a central European latitude. Integrating the differential spectrum with these δ-values gives negligible flux densities for energies below 1 MeV and above 100 MeV. For $T<5$ MeV, the electrons' range is so short (13 m at 3 MeV) that no simulations were executed. (Compare with the height of 15 m of the power lines considered in paper.)

The electromagnetic field

The trajectory simulations are based on Lorentz' Force Law, the theory on which Hopwood's hypothesis rests. Calculating the path of the particles therefore requires an exact knowledge of the electromagnetic field at any point around the power lines. These values are provided by continuous field calculations along the trajectory (actually stepwise as described below for the trajectory simulations). In order to simplify these calculations, the wires of the power line are assumed to be infinitely long and straight and to span over good conducting flat ground. The field values calculated are only valid far from masts and other obstacles.

The outsets for the field calculations are Maxwell's first and fourth equations and the relation between electrostatic field $\boldsymbol{E}$ and potential V ($\boldsymbol{E} = -\nabla V$). The fields around power lines are of course not static. They may, however, be regarded as quasi-static if they fulfil the criterion: $L << c\tau$, where τ is the field period or inverse frequency, c is the speed of light and L the distance from the field source. For ELF-fields (in this case 50 Hz) around the wires, the criterion is fulfilled for any practical distance from the wires. In addition to justifying the use of the electrostatic relation between the electric field and potential, this quasi-static approximation makes it possible to neglect the displacement current component in Maxwell's fourth equation.

Under these assumptions the magnetic field surrounding each wire is circular and can be calculated from the following form of Ampere's Law:

$$B(h) = \frac{\mu_0 i}{2\pi h}.$$

Here μ_0 is the magnetic permeability of free space, *i* the momentary current in the wire of interest and *h* the radial distance between the centre of the wire and the point of field calculation. The field component parallel to the infinite wires (y-component) is zero by symmetry arguments. The total magnetic field is the vector sum of the contributions from all the wires which constitute a transmission line.

The electric field is to be found from Maxwell's First Law, which for a single infinitely long line can be expressed as:

$$E(h) = \frac{\lambda}{2\pi\varepsilon_0 h}.$$

Here ε_0 is the permittivity of free space and λ is an unknown line charge density on the wire. Combining Maxwell's First Law with the electrostatic potential produces:

$$V = -\frac{\lambda}{2\pi\varepsilon_0}\ln h + C,$$

where *C* is an integration constant. For a power line with a three-phase system, the momentary potential *V* for each wire is a known parameter. By exploiting the additivity of electric potential and using the well established method of imaginary mirror charges, one ends up with a set of linear equations. Solving these equations yields the line charge λ for each of the wires. The integration constants disappear when the potential on the ground is defined to be zero, as is customary. The resulting values for λ can now be inserted in the above given form of Maxwell's first equation, and the total electric field is finally found as the vector sum of the contributions from all wires (including mirror images). When calculating charge-densities the charge distribution is assumed to be isotropic over a cross section of the wire. This is not correct, but the error is small when the distance from the wire is large compared to the thickness of the wire (the power lines have a diameter of 0.03 m). Both the wire current *i* and potential *V* (and thereby the charge distribution λ) are time dependent. Due to the high particle speed (approximately speed of light), this time dependence may be disregarded during the passage of a particle. The electromagnetic field is thereby calculated at a constant *phase-time* for each trajectory.

Trajectory simulations in electromagnetic fields

The trajectory simulations are limited to the inside of a defined three dimensional rectangular box, to be known henceforth as a *simulation box* which covers the infinitely long straight power line. Sizing the box is done by trial and error, ensuring that electromagnetic forces do not alter the particles' path outside the box. The starting point for the simulations is the upper level of this box inside of which the Lorentz' force constitutes the dominating influence on the particles, all other forces thereby neglected.

After initiating the simulations with rest mass, phase-time, space and velocity coordinates the further particle trajectory could in principle be calculated exactly by a double time integration over the electromagnetic force. However, since the electromagnetic field, and thereby the Lorentz' force, is a function of space coordinates, this integration cannot be done analytically.

An alternative approach, well suited for computer simulation, is to approximate the exact solution by summing finite differentials. In order to achieve a numerical routine of the second order, the algorithm used in this work is based on a time-centred evaluation of the equations of motion. This means that the calculations of the particles' position and speed are displaced in time. The velocity $v_{t+\Delta t/2}$ of the particle at a time $t+\Delta t/2$ in the algorithm (where Δt

is the finite time differential) is determined from the electric field $\boldsymbol{E}_t$ and the magnetic field $\boldsymbol{B}_t$ at time t and the velocity $\boldsymbol{v}_{t-\Delta t/2}$ at time t-Δt/2. The particles' position $\boldsymbol{r}_{t+\Delta t}$ is evaluated one half of a time-step later ($t + \Delta t$) and is determined from $\boldsymbol{r}_t$ and $\boldsymbol{v}_{t+\Delta t/2}$. This is known as the "leap-frog" method (see e.g. Birsdall and Langdon 1991).

The resulting time-centred expression to be solved for $\boldsymbol{r}_{t+\Delta t}$ is:

$$\boldsymbol{v}_{t+\Delta t/2} = \frac{(\boldsymbol{r}_{t+\Delta t} - \boldsymbol{r}_t)}{\Delta t},$$

where $\boldsymbol{v}_{t+\Delta t/2}$ is to be solved from:

$$m\frac{(\boldsymbol{v}_{t+\Delta t/2} - \boldsymbol{v}_{t-\Delta t/2})}{\Delta t} = q\left(\boldsymbol{E}_t + \frac{(\boldsymbol{v}_{t+\Delta t/2} + \boldsymbol{v}_{t-\Delta t/2})}{2} \times \boldsymbol{B}_t\right).$$

The particle energies considered in this work are no less than 5 MeV, and relativistic effects are consequently highly relevant, accounted for by replacing $\boldsymbol{v}$ by $\boldsymbol{v}\gamma(\boldsymbol{v})$, where the relativistic correction factor γ is a function of the particle speed. Solving this final expression is not a trivial task. The approach used here goes through three steps and includes a separation of the electromagnetic field into one electric and one magnetic component. The method is named the "Boris split-step" method (Birsdall and Langdon 1991).

As this is a second order numerical method, halving the time-step Δt results in a halving of the total calculation error (see e.g. Burden 1989). This means that the simulations can be as exact as one wishes by simply reducing the time-step. A practical choice of Δt is made by trial and error for each simulation.

To save CPU-time during the simulations, two different time-steps were used. When particles are closer than 4.0 m to the wires, a smaller time-step ($1 \cdot 10^{-10}$ s) is used than when they are more distant ($6 \cdot 10^{-10}$ s). This is acceptable since the rate of change of the trajectory decreases fast with increasing distance from the wire. Assuming the particles move with the speed of light, these time-steps correspond to step-lengths of 0.03 m and 0.18 m, respectively.

The algorithm is completed when the particles reach ground level. Here the x-coordinate (horizontal direction perpendicular to the wires) is saved for analysis, while the y-coordinate (horizontal direction along the wire) is ignored due to the symmetry for infinite wires. This simplification to a one-dimensional result, namely the number of particles per area, has to be done at ground level. All three coordinates are necessary during the simulation.

Range

As described above, free electrons are produced continuously down through the atmosphere. They have relatively low energy and a range comparable to the simulated path length. Kinetic energy losses along the simulated trajectory are therefore vital to the simulations (the electromagnetic fields' effect on the trajectory increases substantially with decreasing particle energy). The simulation program takes this into account by continuously reducing the electrons' energy in accordance with the particles' mass stopping power.

An energy dependent function for relevant stopping powers was obtained by curve fitting to tabulated values for mass stopping power in dry air (Attix 1986). By use of this function the reduction in kinetic energy can be found according to the length of the last step and the particles present energy. The energy correction routines are integrated into the algorithm for trajectory simulations.

Simulation sets and initial values

To produce informative and interesting results, the particle simulations must average over phase-time, space and velocity coordinates (velocity coordinates are given by kinetic energy, zenith and azimuth angle). A set of simulations performed for one particle type at a specific energy range which includes this averaging shall be known henceforth as a *simulation set.*

The outset for a simulation set is a number of points at the top of the described simulation box. The points lie at a line perpendicular to the wires and are separated by 0.04 m for $T \leq 10$ MeV and 0.05 m for $T > 10$ MeV. These points define the initial x- and z-coordinates. The y-coordinate is arbitrarily taken to be zero (again due to symmetry for infinite wires). Particles are initiated from each of these points 18 times during a 50 Hz period. For each point, at each phase-time, a number of trajectory simulations are initiated with different energies, zenith and azimuth angles.

The energy range covered by a simulation set is represented by three or four chosen energy levels. The number of particles at each of the levels is determined by integrating a normalised version of the formula describing the differential energy distribution. The resulting number of particles is then used for normalising the distribution function for zenith angles. Applying this function, a representative number of particles can be associated with five to seven chosen zenith angles. The resulting numbers of particles at a given energy and zenith angle combination are tabulated in Tables 1 and 2 for the simulation sets actually presented in this paper. The final parameter left to initiate is the azimuth angle. Since the horizontal distribution is taken to be isotropic, azimuth angles are generated by a random generator.

Allowing a routine in the simulation program to run through all initial values in a simulation set results in 4 to 5 mill simulated trajectories. These are to give a reasonable, statistically representative picture of the real physical conditions.

The space coordinates for the point of impact at ground level are stored for each simulated trajectory. Assembling these results for the whole set of initial values gives the total simulated particle flux. This can in turn be compared with the flux from an environment free from electromagnetic fields. This *background level* of cosmic radiation is achieved by the same simulation program, with the same distribution functions, but without any electromagnetic field.

The final presentation of the results is given as a change in particle flux density in percent. Since the changes are very small (of the order of 0.1 % of the unperturbated flux density), numerical noise is considerable (since there are «only» about 3000 particles in each x interval). A digital filter was therefore utilised on the raw data before presentation. A Blackman finite impulse response filter (Oppenheim and Schafer 1989) with half-values of 2.6 m and 3.2 was used for the results presented in Fig. 3 and 4, respectively.

The power line

The power line chosen for the simulations in this paper has horizontally aligned duplex wires with a phase distance of 9.0 m. All current carrying wires are 15.0 m above ground, while two grounded wires are mounted 22.5 m above ground. This is a typical (Norwegian) 420 kV power line. The current was chosen to carry an extreme, while still realistic 1600 A. All the simulations presented in this paper are based on the electromagnetic field surrounding this power line configuration, voltage and current load. Although this is a power line for much larger energy transports than the one in Hopwood's experiment, it was chosen because its strong electromagnetic field is expected to produce the largest deflections.

RESULTS

To demonstrate the reality of the deflections some complete trajectories are shown as examples in the two first figures. Fig. 1 shows trajectories for electrons which were initiated with a vertical speed corresponding to a kinetic energy of 5 MeV, the lowest initial energy in these simulations. In Fig. 2 the trajectories are shown for 6 MeV electrons with an initial zenith angle of 35°. At this angle, electrons with an energy of 5 MeV have too short a range to reach ground level. To illustrate the deflection's dependence on the phase of the electromagnetic field, the particles in Fig. 2 are initiated 2/3 of a (50 Hz) phase-period later than those in Fig. 1. In both cases the electrons were initiated 0.5 m apart.

Any particle deflection will depend strongly on the strength of the electromagnetic field and on the total energy of the particles. To differentiate the results for different particles and energy ranges, many simulation sets have been executed. However, only the simulations with electrons gave results of common interest and are therefore exclusively presented here. For muons and protons, the deflections were hardly noticeable at this level of accuracy. The special attention to electrons is due to their low total energy and accordingly highest sensitivity to perturbations caused by electromagnetic forces.

The result for a complete simulation set is presented as the relative change in particle flux density from background level as a function of position relative to the centre of the power line. Results from the simulation set for electrons with an energy range of 5-10 MeV are shown in Fig. 3. There is a total of 4.2 mill trajectories behind the presented curve. The initial energies, zenith angles and corresponding number of initial particles are tabulated in Table 1. The low maximum zenith angle for 5-10 MeV electrons is due to their limited range (high zenith angles give long trajectories).

The result can be described as follows: There is a reduced particle flux density at ground level below and just outside the power line. By integrating the results we found that the total flux in the area less than 12 m from just below the centre line is reduced by 0.07% due to the deflection from the power line (0.10% using the data before filtering).

The decrease in particle flux under the power line is matched by an increase in the flux in a band slightly outside this area. Thus, for the low energy electron result in Figure 3, there is an elevated particle flux density in the areas 12-24 m from just below the centre line.

In addition to this main finding, Fig. 3 also shows a hyperfine pattern with several peaks more or less symmetric to the centre line. The reasons for these lines are explained in the Discussion.

Fig. 4 shows the results for electrons with an energy range of 10-100 MeV. Table 2 shows the initial energies and zenith angles which result in a total of 5.2 mill trajectories for the whole simulation set.

The main pattern in the result for the high energy electrons is as for the low energy ones, that is a reduced particle flux under the power line and an increase in the flux outside this area. Integration of the results shows that the total flux in the area less than 13 m from just below the centre line is reduced by 0.04% due to the electromagnetic field. This reduction is matched by a similar increase in the total flux in the area between 13 and 43 m from the centre line (on both sides of the power line). The hyperfine pattern is even more pronounced for the high energy result in Fig. 4 than for low energy electrons in Fig. 3.

The simulation box for 5-10 MeV electrons is smaller than that for 10-100 MeV particles. This is primarily because of the differences in maximum zenith angle (36° vs. 63°). Larger boxes have been used to confirm that the curve stabilises at background level at greater distances from centreline than shown in the figures.

DISCUSSION

The main finding in the results was a reduced particle flux density under the power line and a corresponding increase on the ground outside the line. This is in fact a focusing effect qualitatively similar to the one claimed by Hopwood. Quantitatively Hopwood's results are very, very far from what the theoretical results indicate. Hopwood found up to a doubling of the counting outside the power line. We found at most about 0.2 % for the low energy electrons and even less for the high energy electrons and other particles of interest (see below). Electrons (plus positrons) comprise only about 15 % of the total particle flux; thus, the increase in the total particle flux in any area outside the power line is expected to be well below 0.1 %.

The main finding can be understood by the following simple consideration: A particle that passes very close to a wire might experience a considerable deflection (see Fig. 1 and 2). If its trajectory is accidentally deflected into an area some distance away from the power line, this cannot necessarily be counterbalanced by a particle that is deflected out of this area. The reason is that the electromagnetic fields decrease so fast with the distance from the power line that the deflections occuring some distance from the line are too small to compensate for the deflections taking place very close to the line. The overall effect depends on the zenith angle distribution of the particles.

When it comes to the hyperfine structure our calculations have not given a definite answer as to how much of the structure is due to the discrete set of wires in the power line, and how much is caused by the discrete set of zenith angles used in the calculations. Both factors seem to influence the results. However, the asymmetry from one side of the power line to the other seems to be entirely due to «numerical noise» caused by too few initial azimuth angles (generated by a random generator). The asymmetry can be removed by using a symmetric distribution of fixed azimuth angles. However, fixing these angles to predefined values leads to additional hyperfine structures in the results that are even more annoying than the modest asymmetry.

All in all, the details of the results in Fig. 3 and 4 should not be taken too literally. One can trust the main structure with a reduced flux density below the power line and an increase in the flux density in a band outside this area, since this pattern is found from simulation sets with different initialising conditions. However, the shape of the hyperfine pattern is to some degree incorrect, but a hyperfine pattern will exist because of the spacing between the three phases in the power line.

Simulations have also been performed for different types of power line configurations, voltages and current loads. The main pattern in the results is always the same, but the deflections are, as expected, greatest for the highest current and voltage. Based on these results it is also clear that it is the electric field that is most important for the deflection, even though the magnetic field has a modifying effect.

The simulation sets presented in Fig. 3 and 4 show the changes in electron flux density around a power line. Simulation sets of the same type have been performed for both muons and protons. As mentioned above, deviations from background level were in this case extremely small and easily related to artificial structures attributed to the finite space and velocity distributions. Zero charge neutrons are of course not affected by electromagnetic fields.

The computer program made for simulating the particle trajectories is based on a second order numerical algorithm. Although additional procedures have been added in the source code, the accuracy of the trajectory calculations has only practical limitations in the consumption of computer CPU-time. As an input to the main procedures the calculations of the electromagnetic field is vital. Our calculations will, as mentioned, not be valid close to obstacles and especially not around the masts of the power line. Low humidity in the ground (e.g. sand) may also alter the field values substantially. It is, however, unlikely that neither the general form nor the size of the field can be miscalculated to such an extent that the general structure of the results becomes misleading.

Trustworthy distribution functions for energy and zenith angles are easily available from the literature (see references above), for high energy particles, especially muons. For the interesting and important low energy electrons the published function parameters are scarce and not so well confirmed. Changing the low energy electron spectrum may alter the degree of deviation. However, since the typical relative change for the two simulation sets in this paper differ with roughly by a factor of two (Fig. 3 and 4), it is not likely that minor changes in the electron energy spectrum will alter the observed deflections in a noteworthy way.

Electrons with kinetic energy less than 5 MeV are not treated in this paper since their range is shorter than the height of the simulation box. These low energy particles could experience a deflection far larger than illustrated in Fig. 1 and 2. This will, however, not be observed as a focusing effect at ground level since the electrons do not reach the ground.

The best way to improve the presented results would probably be to increase the number of zenith and azimuth angles in order to get closer to the true hyperfine structure in the flux and to decrease the asymmetry. However, approximating a continuous distribution with a finite representation will necessarily be a compromise between accuracy and available CPU time. The calculations presented in this paper involved several million particles in each set, involving billions of trajectory steps where electric and magnetic fields had to be calculated, as well as calculation of changes in velocity and position and reduction in the energy estimated for obtaining the right range in the air. All this represents a considerable computational task that balances the total available CPU time.

The results in this paper are in agreement with all the experimental works presented after Hopwood's original paper (Burges and Clark 1994; Martinson at al. 1996; Vistnes et al. 1997). In none of these papers was a focusing effect demonstrated. This does not necessarily mean that focusing of particles by a power line does not exist. However, the detectors and techniques used would not be able to point out any effect that led to changes in particle flux of the order of 1%. Thus, the very small focusing effect one can expect from the present paper would be impossible to demonstrate with current available technology.

There is, however, one aspect of the cosmic radiation / power line problem that is not covered by the present work which might be of interest to pursue further. It is well known that acceleration of charged particles leads to emission of electromagnetic radiation. The acceleration can be substantial since the electric field can be up to several hundreds of thousands of volts per meter. Could it be that this effect is responsible for a part of the increase in radio frequency noise that is known to exist near power lines? If so, what is the frequency spectrum of the electromagnetic fields / radiation resulting from the acceleration of cosmic radiation particles?

CONCLUSION

The present paper will hopefully serve as a definitive answer to the hypothesis raised by Antony Hopwood in 1992. Experiments designed to test his findings have not been able to demonstrate any focusing of cosmic radiation around power lines. Nevertheless, the present paper does support the theoretical basis of Hopwood's hypothesis. The actual increase in the particle flux density is, however, found to be within the order of 0.1%, an effect which is probably not measurable with currently available detector technology. From this point of view, our theoretical results are in perfect agreement with the experimental work performed after Hopwood's original paper.

The very small focusing effect will lead to an insignificant change in the total radiation activity and should be of no importance at all in the debate concerning a possible health effect from residing close to power lines.

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REFERENCES

Allkofer, O.C.; Greider, P.K.F. Cosmic Rays on Earth. Kalsruhe: Fachinformationszentrum Energie, Physik, Mathematik GmbH; Physik Daten nr. 25-1; 1984.

Attix, F.H. Introduction to Radiological Physics and Radiation Dosimetry. New York: John Wiley & Sons; 1986.

Brisdall, C.K.; Langdon, A.B. Plasma Physics via Computer Simulation. Bristol: Adam Hilger; 1992.

Burden, R.L. Numerical Analysis. Fourth Edition. Boston, Massachusetts: Pws-Kent; 1989.

Burges, P.; Clark, M. Cosmic radiation and powerlines. Radiol. Prot. Bull. 151:17-19; 1994.

Egeland, A.; Holter, Ø.; Omholt, A. Cosmical Geophysics. Oslo: Universitetsforlaget; 1973.

Hopwood, A. Natural Radiation Focused by Power Lines: New Evidence. Electronic World+ Wireless World Nov 92:912-915; 1992.

Martinson, T.; Wozniak, P.; Norman, J. Power Lines and Ionizing Radiation. Health Phys. 71:944-946; 1996.

Oppenheim, A.V.; Schafer, R.W. Discrete-Time Signal Processing. New Jersey: Prentice-Hall; 1989.

Vistnes, A.I. Abstract G-1-3. Proceedings of the Annual Meeting of the Bioelectromagnetic Society. Los Angeles: Bioelectromagnetics Society, Frederick, MD; 1993.

Vistnes, A.I.; Strand, T.; Thommesen, G. Focusing of cosmic radiation by power lines? Submitted for publication; 1997.

Tables with captions

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Focusing of cosmic radiation....

Table 1 Initial energies and zenith angles for simulations with 5-10 MeV electrons. The numbers of trajectories which are initiated at a given energy and zenith angle combination are tabulated as they are determined from the distribution functions.

	Zenith angle				
Energy (MeV)	4°	12°	20°	28°	36°
5.83	4	10	16	18	20
7.50	2	8	12	14	14
9.17	2	6	8	10	12

Table 2 Initial energies and zenith angles for simulations with 10-100 MeV electrons. The numbers of trajectories which are initiated at a given energy and zenith angle combination are tabulated as they are determined from the distribution functions.

	Zenith angle						
Energy (MeV)	4.8°	14.5°	24.1°	33.8°	43.4°	53.0°	62.7°
17.5	4	10	16	18	16	14	8
32.5	2	4	6	8	8	6	4
47.5		4	4	4	4	2	2
62.5		2	4	4	2	2	

Figure captions

Figure 1 Simulated trajectories for 5 MeV electrons passing a 420 kV - 1600 A duplex power line with a horizontal configuration and phase distance of 9 m. The wires, black spots on the figure, are 15 m above ground, with a direction perpendicularly out of the page. The spacing of the initial particles is 0.5 m.

Figure 2 Simulated trajectories, as for Fig. 1, except for a time displacement of 2/3 of the 50 Hz period and an initial zenith angle of 35°. The electrons are given an initial kinetic energy of 6 MeV in order to have a range long enough to reach the ground

Figure 3 Changes in particle flux density (in percent) at ground level for electrons that were initiated with energies from 5 to 10 MeV. Position is given relative to a point on the ground just below the centre wire of the power line.

Figure 4 Changes in particle flux density (in percent) at ground level for electrons that were initiated with energies from 10 to 100 MeV. Position is given relative to a point on the ground just below the centre wire of the power line.

Figure 1

Skedsmo and Vistnes
Focusing of cosmic radiation....

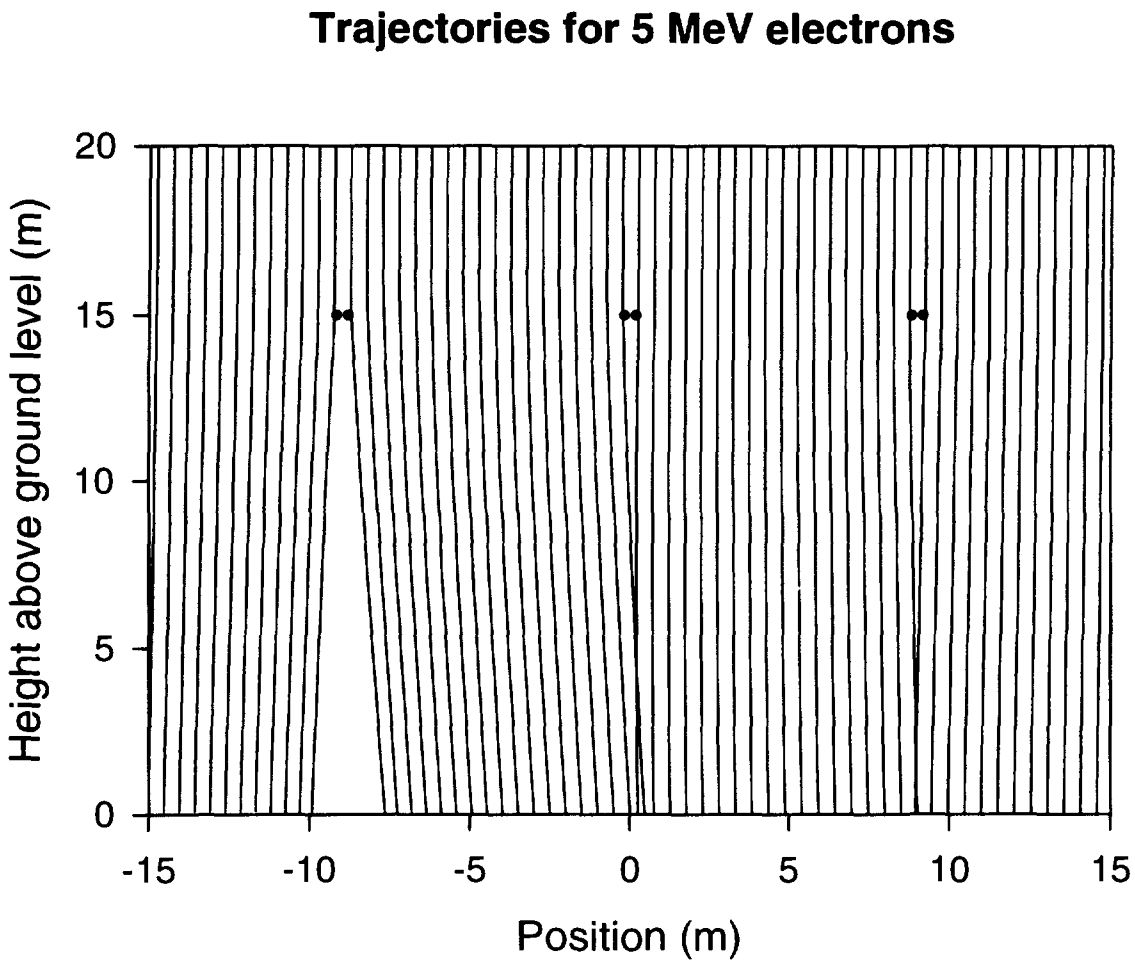


Figure 2

Skedsmo and Vistnes
Focusing of cosmic radiation....

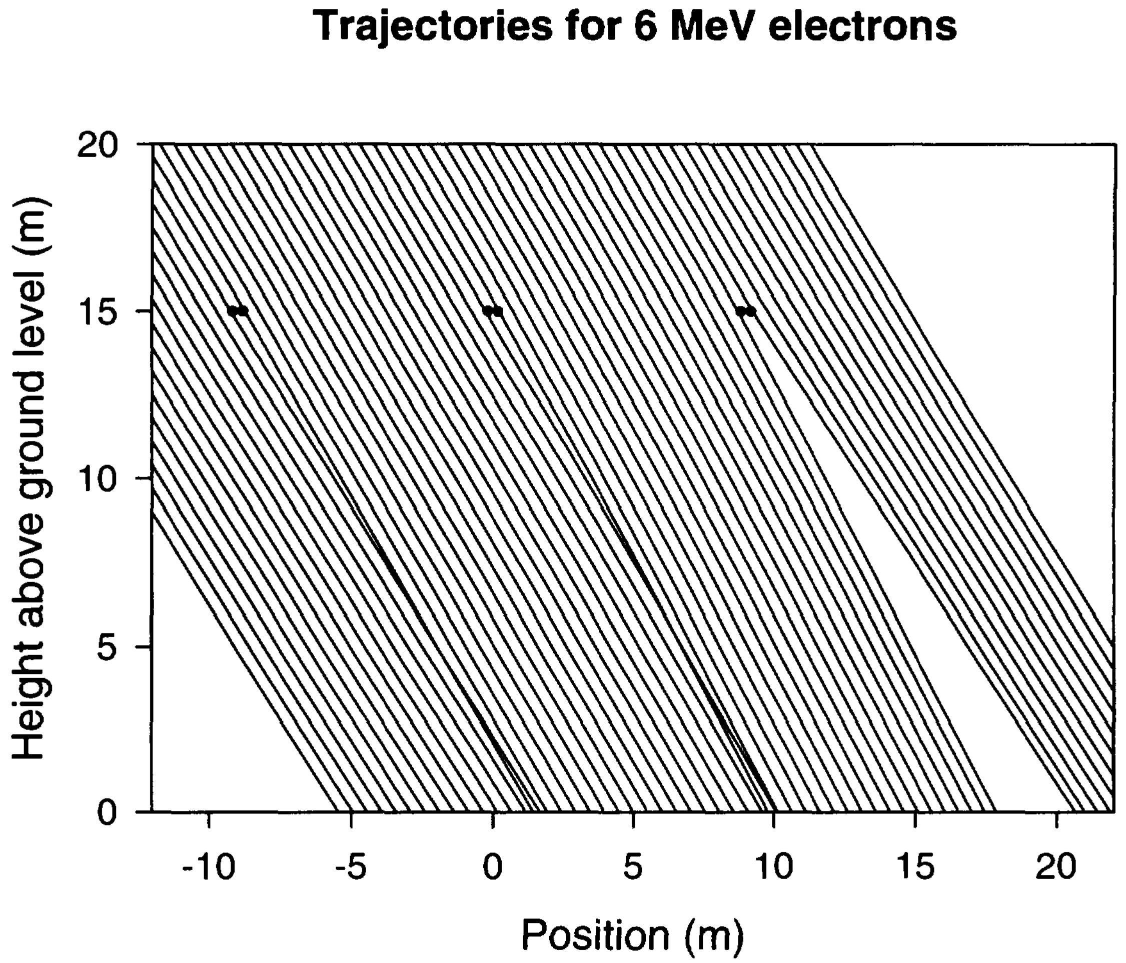


Figure 3

Skedsmo and Vistnes
Focusing of cosmic radiation

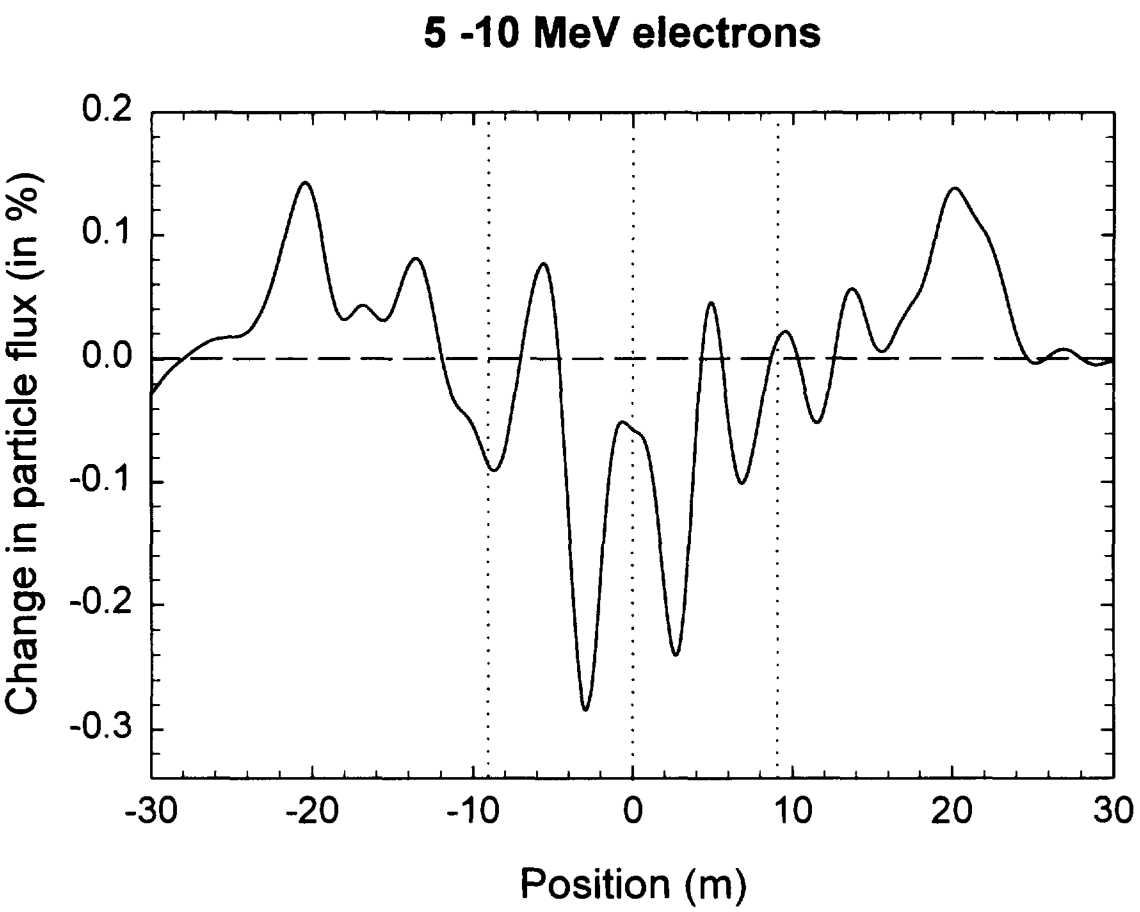
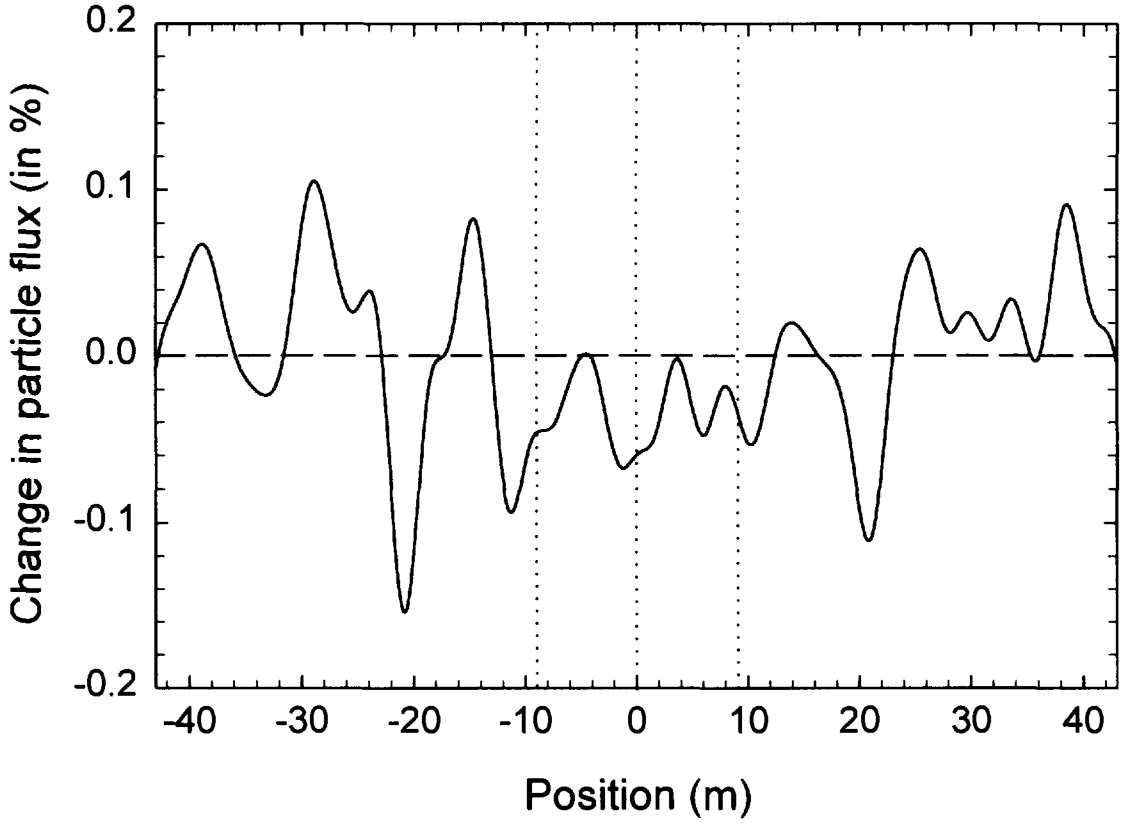


Figure 4

Skedsmo and Vistnes
Focusing of cosmic radiation

10 - 100 MeV electrons



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