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# Feasibility of radar detection of extensive air showers

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ABSTRACT

Reflection of radio waves off the short-lived plasma produced by the high-energy shower particles in the air is simulated, considering various radar setups and shower geometries. We show that the plasma produced by air showers has to be treated always as underdense. Therefore, we use the Thomson cross-section for scattering of radio waves corrected for molecular quenching and we sum coherently contributions of the reflected radio wave over the volume of the plasma disk to obtain the time evolution of the signal arriving at the receiver antenna. The received power and the spectral power density of the radar echo are analyzed. Based on the obtained results, we discuss possible modes of radar detection of extensive air showers. We conclude that the scattered signal is too weak for the radar method to provide an efficient and inexpensive method of air shower detection.



## 1. Introduction

Traditional techniques of extensive air shower detection include recording the shower particles at the ground level or optical methods such as measuring fluorescence light from nitrogen in the atmosphere excited by the shower particles and Cherenkov light of air showers. Detecting radio emission from the shower particles in the MHz–GHz frequency range is a promising new technique that is currently studied, since it offers the possibility of about 100% duty cycle in comparison to only about 15% for optical methods [1–8]. An additional method is the radar technique, in which a ground-based radio transmitter irradiates the ionization trail left behind the shower front and another ground-based antenna receives the scattered radio signal. This remote sensing technology could allow the construction of cosmic ray observatories with very large apertures to be built at much lower cost, with almost 100% duty cycle.

The concept of implementing a radar technique for cosmic ray detection dates back to 1940 [9]. However, due to the lack of experimental confirmation of shower signals, this method was not pursued for several decades. In recent years, renewed attention has been given to this topic [10–19] and experimental efforts to detect cosmic ray showers using the radar technique were made by several groups [20–31].

The radar technique has been used already for decades to observe meteors and lightnings. The detection method is based on the principle of scattering of radio waves off the plasma produced in the atmosphere by the passing meteor or lightning discharge. After the ionization trail is formed, the free electron concentration decreases because of diffusion, atmospheric turbulence, and loss of ionization through recombination and ionic reactions. Among these effects the most important one for meteors is diffusion, which reduces the volume density, but essentially leaves the line density unchanged due to the long ionization trails of meteors.

Meteors are observed at altitudes of 80 to 120 km and their typical velocities are in the range of 10 to 70 km/s. The ionization trails produced by them have long lifetimes, thus they can extend over several kilometers and have an initial radius of order of 1 m up to even 10 m. The ionization column of a meteor has an approximately uniform radial distribution of density and a line density of electrons between $10^{11}$ and $10^{14}$ cm$^{-1}$ [32]. The plasma electrons can be considered to be in thermal equilibrium with the ambient atmosphere except for the very early stages of the formation of the meteor trail. Densities of the ionization trails produced by lightnings are many orders of magnitude higher than those produced by meteors and the plasma channels are of much smaller sizes.

The ionization trail that results from meteors or lightnings is traditionally divided into the underdense and overdense regions, depending on the local characteristic plasma frequency $\omega_p$. If the electron density is high enough that the plasma frequency exceeds the radar frequency, i.e. the frequency of the emitted radio wave, then the radio wave is reflected from its surface. Such a region is called

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overdense. In contrast, if the electron density is low enough that the local plasma frequency is lower than the frequency of the incoming radio wave, then the region is underdense and the radio wave can penetrate the ionized region. In such a case the reflections by scattering of the radio wave off individual free electrons has to be considered. For radar frequencies used in meteor science, the limiting density between these two regimes is around the ionization line density of $10^{12}$ cm$^{-1}$.

Gorham [11] considered radar reflection from the side of a horizontal ionization trail left by an air shower caused by ultra-high energy neutrinos at an altitude of about 10 km. He suggested that the most inner (densest) part of the ionization column is responsible for the bulk of the radar reflection. In analogy with the reflective behavior of the overdense region produced by a meteor, he assumed that the radar cross-section of the overdense trail produced by a shower corresponds to the radar cross-section of a thin metallic wire.

An alternative mode of shower detection was discussed in [13,14], where reflection of the radar wave from the relativistically moving shower front was considered. The reflection coefficient was obtained by solving the Maxwell equations with the corresponding boundary conditions. In this mode of detection, the frequency of the radar echo is higher than the frequency of the incoming wave, in contrast to the reflection from the side of the ionization trail, where the frequency change is very small.

Scattering of a radio wave from the ionization trail produced by a shower in the underdense plasma regime was considered in [15]. The calculations were made for the forward scattered signal assuming that the ionization occurs in a line along the shower axis, i.e. that contributions from the laterally distributed electrons are coherent. The transmitter and receiver were located 50 km apart.

Finally, Filonenko [18] calculated the signal reflected from the plasma disk produced at the shower maximum at altitude of about 4 km. He solved the equation of motion of plasma electrons in the electromagnetic field, accounting for electron collisions with neutral molecules.

The ionization trail that is produced in the atmosphere by the passage of the high-energy particles of a shower (shower front), consists of electrons, which are essentially at rest with respect to the surrounding atmosphere. The plasma decays exponentially with the lifetime that depends on the air density and is equal to 15 ns at sea level [33,34], whereas the radial dependence of its density is controlled by the lateral distribution of the shower energy deposition in the air. The electron density is highest at the shower axis and decreases steeply with the distance from it. The diameter of the ionization trail is of several hundred meters. The shower front moves approximately with the speed of light in vacuum. Due to the short lifetime of the created plasma, the plasma-filled region behind the shower front also moves with the speed of light even though the electrons of the plasma do not move on macroscopic scales. Therefore, a Doppler effect will be observed in the radar echo, unless the shower is seen from the side. An enhancement of the signal scattered backwards due to its time compression is also expected.

In this paper, which is an extension of our previous work [16,17], we investigate the feasibility of detecting extensive air showers by the radar technique. Simulations are performed for the underdense regime using the Thomson cross-section for scattering of radio waves off the short-lived, non-moving plasma, with a correction for molecular quenching. We sum coherently the reflected radio waves off the individual electrons over the volume of the disk-like ionization trail and obtain the time evolution of the radar echo.

As an application we will consider the feasibility of supplementing a microwave detector [4–7] with a radio transmitter and using the microwave antennas (tuned to the GHz frequency band) as receivers for the radar echo. Furthermore, we will check whether the CROME (Cosmic Ray Observation via Microwave Emission) results

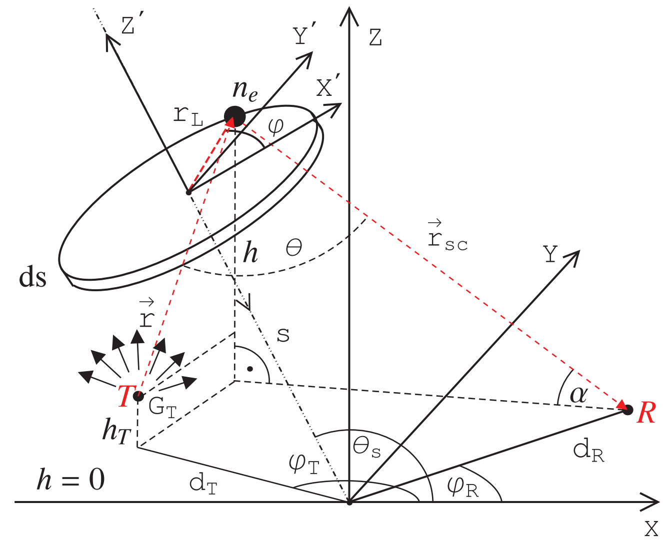


**Fig. 1.** Schematic diagram representing the considered radar system and reflection from the plasma disk produced by a shower in the atmosphere. A ground-based radio transmitter ($T$) emits a radio signal, which is scattered off an element of the plasma disk and subsequently observed by the receiver antenna ($R$). The geometry of the radar system is determined by the distances from the shower core to the transmitter ($d_T$) and to the receiver ($d_R$) together with their azimuth angles ($\varphi_T$ and $\varphi_R$) and the altitude of the transmitter ($h_T$).

[7,8,35] could be interpreted as the radar reflection from the plasma produced by the shower in the air.

The outline of the paper is as follows. In Section 2 we describe the details of our calculations. Section 3 contains an extensive discussion of the plasma properties. In Section 4 we describe the simulations performed and present the analysis of the radar echo. The results and accuracy of the current approach to the problem of the air shower detection by radar is discussed in Section 5. Finally, the Appendix contains the detailed derivation of the formulae from Section 2.

## 2. Modeling radar reflection

### 2.1. Calculation of the radar signal

A schematic diagram representing the concept of extensive air shower detection using the radar technique is shown in Fig. 1. A ground-based radio transmitter ($T$) irradiates a disk-like static plasma left behind the shower front. The radio signal is scattered by free electrons in the ionization trail and subsequently received by the ground-based antenna ($R$). The geometry of such a radar system is described conveniently by the cylindrical coordinates of the transmitter and the receiver, i.e. by the distances from the shower core to the transmitter ($d_T$) and to the receiver ($d_R$), and by the angles $\varphi_T$ and $\varphi_R$. The altitude of the transmitter is given by $h_T$, whereas the receiver is at the ground level.

The system of coordinates $XYZ$ is chosen in such a way that the plane constructed by the $X$-axis and the shower axis is perpendicular to the ground. Moreover, the $X$ and $Y$ axes lie at the ground level. The center of the coordinate system is placed at the shower core, i.e. at the point of intersection of the shower axis with the ground. The coordinate system of the disk-like static plasma $X'Y'Z'$ is simply created by rotating the $XYZ$ frame of reference around $Y$-axis by the shower inclination angle $|\theta_s - \pi/2|$ and translating the resulting system of coordinates along $Z'$-axis by $s$.

The disk in Fig. 1, which is perpendicular to the shower axis, represents a slice of the static plasma. Its distance to the shower core at ground is equal to $s$. In the following we will consider a plasma