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Electromagnetic scattering of charged particles in a strong wind-blown sand electric field*

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Some field experimental results have shown that the moving sands or dust aerosols in nature are usually electrified, and those charged particles also produce a strong electric field in air, which is named as wind-blown sand electric field. Some scholars have pointed out that the net charge on the particle significantly enhances its electromagnetic (EM) extinction properties, but up to now, there is no conclusive research on the effect of the environmental electric field. Based on the extended Mie theory, the effect of the electric field in a sandstorm on the EM attenuation properties of the charged larger dust particle is studied. The numerical results indicate that the environmental electric field also has a great influence on the particle's optical properties, and the stronger the electric field, the bigger the effect. In addition, the charged angle, the charge density, and the particle radius all have a specific impact on the charged particle's optical properties.

Keywords: wind-blown sand, electric field, extended Mie theory, charged particle, scattering

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1. Introduction

Due to the negative impacts of aerosol on environment, climate, and ecosystem appearing,[1] some researchers begin to pay much more attention to the aerosol, especially in atmospheric science.[2] The sand/dust particle is an important composition of aerosols. In some related research processes, for example, the remote sensing of sandstorm and other aerosols, it is extremely important to accurately forecast the particle's optical properties.[3,4] Therefore, some analytical solutions and the numerical simulation method have been proposed by many scholars.[3,5–8] However, in some cases, these methods can provide the accurately prediction results for the attenuation of electromagnetic (EM) wave in sandstorms,[9,10] in others, it maybe fails,[11] and there has been no any reasonable explanation until 2005. Some physical experiments of wind-blown sand have proved that the moving sands carry amounts of static charge, which also produce a strong electric field in the air,[12–14] the maximal intensity can reach up to 200 kV/m.[15,16] The theoretical researches, based on the Rayleigh approximation[17,18] or the Mie theory,[19–22] have shown that the charge on the particle surface can influence the optical properties of the particle,[23] and both the distribution angle and the surface density of the net charge have significant effects.[17–20,24,25] However, there have been no reports on the effect of the electric field so far.

Generally speaking, the dielectric particle immersed in an electric field will be polarized, its surface must have some polarization charge, and the magnitude is proportional to the strength of the electric field. If the electric field is strong enough, the order of magnitude of the polarization charge and the surplus charge will be the same. Therefore, they both can affect the particle's optical properties. Nonetheless, there are no related reports published.

In view of this situation, this paper presents a theoretical model to discuss the effects of the environmental electric field on particle's extinction properties. Firstly, the polarization charge is derived from the knowledge of electrostatics, and then the extinction efficiency of the charged particle immersed in a strong electric field is discussed. At the last, the effects of the distribution angle and the surface density of the net charge are analyzed.

2. The basically physical models

2.1. The polarization charge

As shown in Fig. 1, a partially charged spherical sand is immersed in an electric field of wind-blown sand. In this paper, we suppose that the particle radius is R and the permittivity is ε_1. The surplus charge partially distributes on the particle, and the charge density is σ_0, which uniformly distributes on a spherical cap of the sand, and the net charge distribution angle is $2\theta_0$. The environmental medium is the air. The magnitude of the environmental electric field is E_p. Due to the

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electric polarization, the electric potentials inside and outside of the particle are ψ_1 and ψ_2, which can be expressed in the spherical coordinate as follows:[18]

$$\psi_1 = \sum_n A_n r^n P_n(\cos\theta), \tag{1}$$

$$\psi_2 = \sum_n (C_n r^n + D_n r^{-(n+1)}) P_n(\cos\theta). \tag{2}$$

Here $P_n(\cos\theta)$ is the Legend function of the first kind, and A_n, C_n, and D_n are the unknown expansion coefficients, which can be determined by the boundary conditions

$$r = R: \quad \psi_1 = \psi_2 \varepsilon_1 \frac{\partial \psi_1}{\partial r} - \varepsilon_0 \frac{\partial \psi_2}{\partial r} = \sigma_1 H_{(\theta-\theta_0)}, \tag{3}$$

$$r \to \infty: \quad \boldsymbol{E} = E_\rho \hat{\boldsymbol{z}} = \hat{\boldsymbol{r}} E_\rho \cos\theta - \hat{\boldsymbol{\theta}} E_\rho \sin\theta. \tag{4}$$

Here ε_0 is the permittivity of the environmental medium, and $H_{(\theta-\theta_0)}$ is the Heaviside function.[17] In this paper, we use a spherical polar coordinate system with coordinates (r,θ,φ) and a rectangular coordinate system with coordinates (x,y,z), the corresponding unit base vectors are $(\hat{\boldsymbol{r}},\hat{\boldsymbol{\theta}},\hat{\boldsymbol{\varphi}})$ and $(\hat{\boldsymbol{x}},\hat{\boldsymbol{y}},\hat{\boldsymbol{z}})$, respectively.

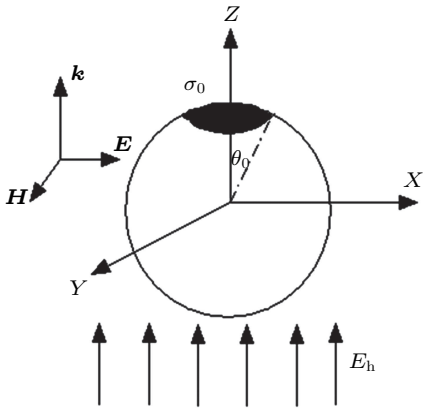


Fig. 1. Schematic drawing of partially charged sand in E-field illuminated by the EM wave.

Through Eqs. (1)–(4) and set $\varepsilon_r = \varepsilon_1/\varepsilon_0$, we can obtain the potential functions as follows:

$$\psi_1 = \frac{\sigma_1 R}{\varepsilon_0} H_{(\theta-\theta_0)} - \frac{3}{\varepsilon_r+2} E_\rho r\cos\theta, \tag{5}$$

$$\psi_2 = \frac{\sigma_1 R^2}{r\varepsilon_0} H_{(\theta-\theta_0)} - E_\rho r\cos\theta + \frac{\varepsilon_r-1}{\varepsilon_r+2}\frac{E_\rho r\cos\theta}{r^2}. \tag{6}$$

The inner electric field of the charged particle is

$$\boldsymbol{E}_{in} = -\nabla\psi_1 = \frac{3}{\varepsilon_r+2} E_\rho \hat{\boldsymbol{x}} + \frac{\sigma_1 R}{r\varepsilon_0}\delta_{(\theta-\theta_0)}\hat{\boldsymbol{\theta}}. \tag{7}$$

Then based on the equation $\boldsymbol{P} = \varepsilon_0(\varepsilon_r - 1)\boldsymbol{E}_{in}$ and $\sigma_p = \hat{\boldsymbol{r}}\cdot\boldsymbol{P}$, we can obtain the expression of the polarization charge[26]

$$\sigma_p = \hat{\boldsymbol{r}}\cdot\boldsymbol{P} = 3E_\rho\varepsilon_0\frac{\varepsilon_r-1}{\varepsilon_r+2}\cos\theta. \tag{8}$$

Considering the net charge on the particle surface is σ_0 which partially distributes on a cap of the sphere, the total charge on the particle is $\sigma = \sigma_0 H_{(\theta-(\pi-\theta_0))} + \sigma_p$. In the next section, we will set it as a constant for every θ.

2.2. The extended Mie theory for partially charged sphere

Suppose that the incident wave is a z propagating plane wave characterized by the wave vector $\boldsymbol{k} = k\hat{\boldsymbol{z}}$, where $k = 2\pi/\lambda$ is the wave number, and λ is the wavelength. The electric field vector of the incident wave is $\boldsymbol{E}_{inc} = E_0\exp(\mathrm{i}kz)\boldsymbol{x}$. The electromagnetic field of the incident wave can be expanded as follows:[27]

$$\begin{aligned}\boldsymbol{E}_{inc} &= -\sum_{n=0}^{\infty}\sum_{m=-n}^{n}\mathrm{i}E_{mn}\left[p_{mn}\boldsymbol{N}_{mn}^{(1)}(\rho,\theta,\varphi)\right.\\ &\quad\left.+q_{mn}\boldsymbol{M}_{mn}^{(1)}(\rho,\theta,\varphi)\right],\end{aligned} \tag{9}$$

$$\begin{aligned}\boldsymbol{H}_{inc} &= -\frac{k}{\omega\mu_0}\sum_{n=0}^{\infty}\sum_{m=-n}^{n}E_{mn}\left[q_{mn}\boldsymbol{N}_{mn}^{(1)}(\rho,\theta,\varphi)\right.\\ &\quad\left.+p_{mn}\boldsymbol{M}_{mn}^{(1)}(\rho,\theta,\varphi)\right],\end{aligned} \tag{10}$$

$$E_{mn} = E_0\mathrm{i}^n\left[\frac{(2n+1)(n-m)!}{n(n+1)(n+m)!}\right]^{1/2},$$

where $\rho = kr$, $\boldsymbol{N}_{mn}^{(1)}(\rho,\theta,\varphi)$ and $\boldsymbol{M}_{mn}^{(1)}(\rho,\theta,\varphi)$ are the vector spherical harmonics functions, and can be represented as follows:

$$\begin{aligned}&\boldsymbol{N}_{mn}^{(j)}(\rho,\theta,\varphi)\\ &= \hat{\boldsymbol{r}}n(n+1)P_n^m(\cos\theta_p)\frac{z_n(\rho)}{\rho}\exp(\mathrm{i}m\varphi)\\ &\quad+\left[\hat{\boldsymbol{\theta}}\frac{\mathrm{d}P_n^m(\cos\theta)}{\mathrm{d}\theta}+\hat{\boldsymbol{\varphi}}\mathrm{i}\frac{P_n^m(\cos\theta)}{\sin\theta}\right]\frac{1}{\rho}\frac{\mathrm{d}}{\mathrm{d}\rho}[\rho z_n(\rho)]\exp(\mathrm{i}m\varphi),\\ &\boldsymbol{M}_{mn}^{(j)}(\rho,\theta,\varphi)\\ &= \left[\hat{\boldsymbol{\theta}}\mathrm{i}\frac{P_n^m(\cos\theta)}{\sin\theta}-\hat{\boldsymbol{\varphi}}\frac{\mathrm{d}P_n^m(\cos\theta)}{\mathrm{d}\theta}\right]z_n(\rho)\exp(\mathrm{i}m\varphi).\end{aligned}$$

Here $P_n^m(\cos\theta)$ is the associated Legend function of the first kind, and for the function $z_n(\rho)$ in $\boldsymbol{N}_{mn}^{(j)}(\rho,\theta,\varphi)$ and $\boldsymbol{M}_{mn}^{(j)}(\rho,\theta,\varphi)$, if $j=1$, the function $z_n(\rho)$ is the spherical Bessel function of the first kind, named as $j_n(\rho)$, if $j=2$, the function $z_n(\rho)$ is the spherical Bessel function of the second kind, named as $y_n(\rho)$, and if $j=3$, the function $z_n(\rho)$ is the spherical Bessel function of the third kind, named as $h_n^{(1)}(\rho) = j_n(\rho) + \mathrm{i}y_n(\rho)$, with i being the imaginary unit. Then the interior field and the scattering field can also be written in the similar forms

$$\begin{aligned}\boldsymbol{E}_s &= \sum_{n=0}^{\infty}\sum_{m=-n}^{n}\mathrm{i}E_{mn}[a_{mn}\boldsymbol{N}_{mn}^{(3)}(\rho,\theta,\varphi)\\ &\quad+b_{mn}\boldsymbol{M}_{mn}^{(3)}(\rho,\theta,\varphi)],\end{aligned} \tag{11}$$

$$\begin{aligned}\boldsymbol{H}_s &= \frac{k}{\omega\mu_0}\sum_{n=0}^{\infty}\sum_{m=-n}^{n}E_{mn}[b_{mn}\boldsymbol{N}_{mn}^{(3)}(\rho,\theta,\varphi)\\ &\quad+a_{mn}\boldsymbol{M}_{mn}^{(3)}(\rho,\theta,\varphi)],\end{aligned} \tag{12}$$

$$\boldsymbol{E}_1 = -\sum_{n=0}^{\infty}\sum_{m=-n}^{n}\mathrm{i}E_{mn}[c_{mn}\boldsymbol{N}_{mn}^{(1)}(\rho,\theta,\varphi)$$

$$+d_{mn}\boldsymbol{M}_{mn}^{(1)}(\rho,\theta,\varphi)], \tag{13}$$

$$\boldsymbol{H}_1 = -\frac{k_1}{\omega\mu_1}\sum_{n=0}^{\infty}\sum_{m=-n}^{n}E_{mn}[d_{mn}\boldsymbol{N}_{mn}^{(1)}(\rho,\theta,\varphi) + c_{mn}\boldsymbol{M}_{mn}^{(1)}(\rho,\theta,\varphi)]. \tag{14}$$

The unknown coefficients can be determined by the boundary conditions[19,21]

$$\begin{aligned}&[\varepsilon_0(\boldsymbol{E}_\mathrm{s}+\boldsymbol{E}_\mathrm{inc})-\varepsilon_1\boldsymbol{E}_1]\cdot\hat{\boldsymbol{n}}=\sigma,\\ &[\mu_0(\boldsymbol{H}_\mathrm{s}+\boldsymbol{H}_\mathrm{inc})-\mu_1\boldsymbol{H}_1]\cdot\hat{\boldsymbol{n}}=0,\\ &\hat{\boldsymbol{n}}\times[(\boldsymbol{E}_\mathrm{s}+\boldsymbol{E}_\mathrm{inc})-\boldsymbol{E}_1]=0,\\ &\hat{\boldsymbol{n}}\times[(\boldsymbol{H}_\mathrm{s}+\boldsymbol{H}_\mathrm{inc})-\boldsymbol{H}_1]=\sigma^\mathrm{s}\boldsymbol{E}_1.\end{aligned} \tag{15}$$

Here σ^s is the surface conductivity, which can be obtained through the equation $\sigma^\mathrm{s}(\sigma)=\mathrm{i}\sigma q/[m(\omega+\mathrm{i}r_\mathrm{s})]$, and $r_\mathrm{s}=\pi Nr^2\sqrt{T/m}$, σ is the surface charge density which can be derived from $\sigma=\sigma_0 H_{(\theta-(\pi-\theta_0))}+\sigma_\mathrm{p}$ present in the last section. m, q, and r are the mass, charge, and radius of the electron, respectively, N is the electron number, and T is the surface temperature.

In principle, the electric polarization means that the positive charge in the material moves along the direction of the applied electric field, and the negative charge (usually, electrons) is reversed moving, thus one half of the particle surface is positively charged, the other half is negatively charged. For the nuclei, it is too large to produce a surface current with the action of the incident electromagnetic wave, but the electron can. So the valid charge which may contribute to the surface conductivity is just the negative ion ($\sigma_\mathrm{p}<0$). This means that the surface conductivity in Eq. (15) can be expressed as two parts, one is from the net charge, which can be calculated through $\sigma^\mathrm{s}(\sigma_0 H(\theta-(\pi-\theta_0)))$, and the other one is from the polarization, which can be calculated from $\sigma^\mathrm{s}\left(\sigma_\mathrm{p}H(\theta-\pi/2)\right)$. Here we have set σ_0 as the net charge on the particle surface, σ_p as the polarization charge in Eq. (9), where $H(x)$ is the Heaviside function.

Then through Eqs. (9)–(15) we can obtain

$$\begin{aligned}&j_n(mx)c_{mn}+h_n^1(x)b_{mn}=j_n(x)q_{mn},\\ &[mxj_n(mx)]'d_{mn}+m[xh_n^1(x)]'a_{mn}=m[xj_n(x)]'p_{mn},\\ &\{[mxj_n(mx)]'c_{mn}+[xh_n^1(x)]'b_{mn}-[xj_n(x)]'q_{mn}\}\Pi\\ =\;&(\mathrm{i}\omega\sigma_\mathrm{s}\mu_1 Rj_n(mx)\Pi_0+\mathrm{i}\omega\sigma_\mathrm{ps}\mu_1 Rj_n(mx)\Pi_{\pi/2})c_{mn}\\ &-\left(\Gamma\frac{\sigma_\mathrm{s}}{mx}\omega\mu_1\mathrm{R}[mxj_n(mx)]'\right.\\ &\left.+\Gamma_{\pi/2}\frac{\sigma_\mathrm{ps}}{mx}\omega\mu_1\mathrm{R}[mxj_n(mx)]'\right)d_{mn},\\ &\{mxj_n(mx)d_{mn}+xh_n^1(x)a_{mn}-xj_n(x)p_{mn}\}\Pi\\ =\;&-\left(\Gamma\sigma_\mathrm{s}R\omega\mu_1 j_n(mx)+\Gamma_{\pi/2}\sigma_\mathrm{ps}R\omega\mu_1 j_n(mx)\right)c_{mn}\\ &+\left(\mathrm{i}\omega\sigma_\mathrm{s}\mu_1 R\frac{[mxj_n(mx)]'}{mx}\Pi_0\right.\\ &\left.+\mathrm{i}\omega\sigma_\mathrm{ps}\mu_1 R\frac{[mxj_n(mx)]'}{mx}\Pi_{\pi/2}\right)d_{mn},\\ &\Pi=\int_0^\pi\pi_{mn}\pi_{mn}\sin\theta\,\mathrm{d}\theta,\quad \Pi_0=\int_{\pi-\theta_0}^\pi\pi_{mn}\pi_{mn}\sin\theta\,\mathrm{d}\theta,\\ &\Gamma=\int_{\pi-\theta_0}^\pi\pi_{mn}\tau_{mn}\sin\theta\,\mathrm{d}\theta,\quad \Pi_{\pi/2}=\int_{\pi/2}^\pi\pi_{mn}\pi_{mn}\sin\theta\,\mathrm{d}\theta,\\ &\Gamma_{\pi/2}=\int_{\pi/2}^\pi\pi_{mn}\tau_{mn}\sin\theta\,\mathrm{d}\theta,\\ &\sigma_\mathrm{s}=\sigma^\mathrm{s}(\sigma_1),\quad \sigma_\mathrm{ps}=\sigma^\mathrm{s}(\sigma_\mathrm{p}).\end{aligned} \tag{16}$$

Through the above equations, we can obtain the expansion coefficients in Eqs. (9)–(14).

Then the particle's extinction cross section can be obtained as

$$C_\mathrm{ext}=\frac{\frac{1}{2}\mathrm{Re}\int_0^{2\pi}\int_0^\pi(E_{\mathrm{i}\varphi}H_{\mathrm{s}\theta}^*-E_{\mathrm{i}\theta}H_{\mathrm{s}\varphi}^*-E_{\mathrm{s}\theta}H_{\mathrm{i}\varphi}^*+E_{\mathrm{s}\varphi}H_{\mathrm{i}\theta}^*)r^2\sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi}{\frac{1}{2}k|E_0|^2/(2\omega\mu)}, \tag{17}$$

where subscripts i and s represent the incident field and the scattering field, and subscripts θ and φ represent the components of the field. The extinction cross section can be normalized by the particles' geometric cross section, and then we can obtain the efficiency factor

$$Q_\mathrm{ext}=C_\mathrm{ext}/(\pi R^2). \tag{18}$$

In the next section, we will use Eqs. (16)–(18) to discuss the electromagnetic scattering properties of the partially charged particle in a strong electric field.

3. Results and discussion

The parameters in the numerical calculation are as follows: the frequency of the incident wave is 9.4 GHz, the particle radius is 30 μm, the relative refractive index $m=1.5+0.1\mathrm{i}$, the relative permittivity $\varepsilon_\mathrm{r}=m^2$. The net charge density $\sigma_0=-1\ \mu\mathrm{C/m^2}$, and the intensity of the environmental electric field is $E_\mathrm{h}=100\ \mathrm{kV/m^2}$. Without any special comments, the parameters remain unchanged.

Firstly, the effect of the electric field on the sand's extinction efficiency is discussed, and the results are showed in Fig. 2. The horizontal coordinate is the logarithmic coordinate system, but the vertical coordinate is the rectangular coordinate system. From it we can know that when the intensity of the environmental electric field is larger than 3 kV/m, the effect of the electric field on the particle optical properties is significant, and with the electric field increasing, the effect becomes much stronger.

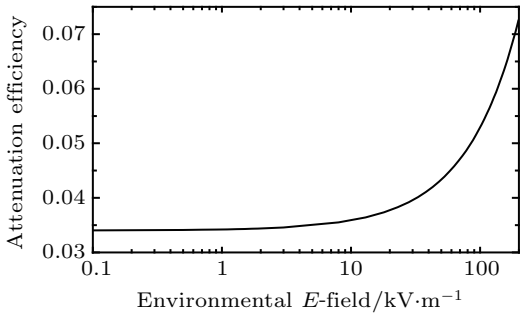


Fig. 2. The effect of environmental electric field on particle's extinction efficiency.

In Fig. 3, the effect of the charge distribution angle on sand's extinction efficiency is discussed, and we set the intensity of environmental electric field as 100 kV/m. The results show that, for a given charge density, the particle extinction efficiency firstly increases and then decreases with the charge distribution angle increasing, and when the charge distribution angle is 110°, it arrives at a maximal value. In addition, it is worth noting that the extinction efficiency of the charged sand in an electric field is much larger than the one without considering the effect of the environmental electric field.

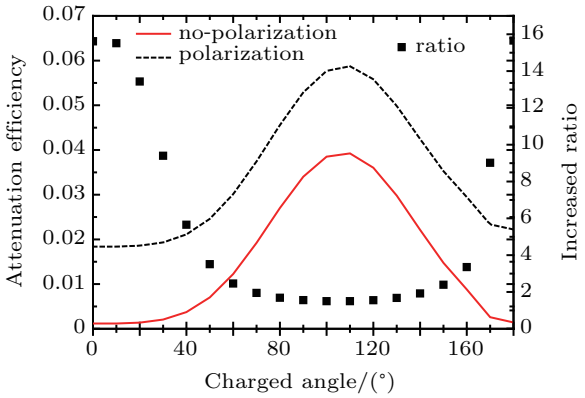


Fig. 3. The effect of charge distribution angle on particle extinction efficiency in electric field.

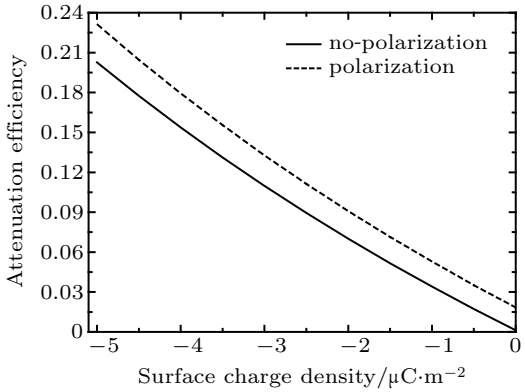


Fig. 4. The effect of charge density on particle's extinction efficiency in electric field.

The effect of the charge density is shown in Fig. 4. It can be seen that the particle extinction efficiency linearly increases with the increase of the surface charge density on the particle, and the values are much larger than those when the polarization charge is not unconsidered. Figure 5 reveals the effect of the particle radius on the optical properties. From it we can know that the particle extinction efficiency exponential changes with the increase of the particle's radius, and the extinction efficiency when considering the polarization charge in strong electric field is much larger.

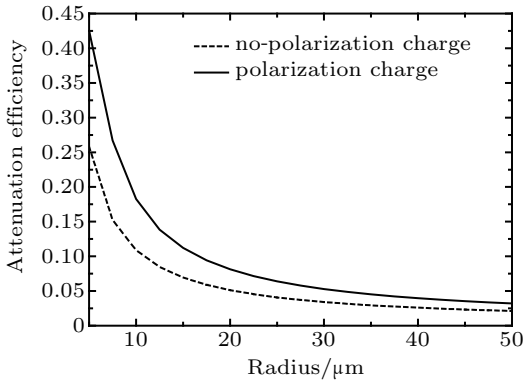


Fig. 5. The effect of particle radius on particle's extinction efficiency in electric field.

4. Conclusion

Based on the extended Mie theory, the effect of the electric field in dust/sand storm on the sand's optical properties is investigated. It is found that for the charged sand particle in sand storm with strong electric field, its optical properties are significantly influenced by the environmental electric field, and when the electric field exceeds 3 kV/m, the particle's extinction efficiency enhances with the increase of the electric field intensity. The charged angle, charge density, and particle radius all have specific impact on the influence of electric field in charged sand's optical properties. These results are important for the analysis of laboratory data and remote sensing information on sandstorm and rain-cloud parameters.

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