Radiation scattering on growing ordered structures

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Abstract. Local order of scattering medium is essential in multiple-scattering problem. It causes coherent effects in light scattering character. We consider scattering phase function computation for growing ordered structure, i.e. cluster formation. The computational results illustrate a deformation of scattering phase function and its transformation during the growth of particle cluster as well as the energy and peak characteristics of this process, which indicate the possibility to determine the generalized equations for scattering phase function depending only on form- and structure-factor. We study multiple scattering on structured media consisted of different clusters using Monte Carlo numerical approach. The cluster phase function has direct impact on scattered radiation, moreover, for media consisted of different clusters the middle-cluster approach is estimated.

1. Introduction
In local-ordered scattering media (clusters, quasi-crystals, etc.) dense location of particles leads to multiple scattering character with coherent effects [1]. It is relevant for fundamental and applied problems of remote sensing, biological fluids analysis, ecology [2–7]. Moreover, for various applications of terahertz (THz) technology [8–12], multiple scattering in ordered structures has an essential influence on interaction between radiation and medium [13–15]. In such case locally ordered particle group plays a significant role in determination of the single-scattering phase function, structure factor, and overall distribution of the scattered radiation [16].

In the present work we consider the scattering groups of particles (clusters) with dielectric properties and study THz scattering on them. The number of particles in cluster is increasing, along with the local order, which changes the scattering phase function $\chi(\theta)$, where $\theta$ is the scattering angle. Using the numerical methods of finding $\chi(\theta)$ we analyze its deformation during cluster growing process. Using Monte Carlo (MC) numerical modeling we study radiation scattering on a layer consisted of particle clusters of single and various types.

2. Transformation of scattering phase function
We consider 2D scattering clusters of particles with diameter $d = \lambda/10$ and dielectric permittivity $\varepsilon = 2.5$. The incident radiation has the wavelength $\lambda = 1.2$ mm. Figure 1 illustrate spatial symmetry and the parameters of these clusters. Since the number of particles increases, the cluster region diameter $D$ is a variable parameter.

Using the numerical methods of finding $\chi(\theta)$ [17], we calculate a set of scattering phase functions for growing clusters. These results are presented in the figure 2 (a) and (b). Phase functions have strong secondary peaks, which is a consequence of coherent effects. Since the
cluster symmetry is not changed, the directions of secondary peaks remain the same. The scattering peaks become more sharp during cluster growing, furthermore, for large clusters scattering phase function consists mostly of several peaks with other peaks suppressed.

Figures 2(c) and (d) demonstrate changes of the scattered radiation energy in main peaks and semiwidth of the forward scattering peaks, respectively. We can notice that hexagonal as well as quadratic structures show similar dependence of energy and angular characteristics transformation. It is determined by particle and cluster dimensions and dielectric parameters of particles and external media (here we consider vacuum as an external medium). Using such dependencies and initial phase function for small cluster, we can predict scattering characteristics of clusters made of arbitrary number of particles.

Figure 2. Transformation of the scattering phase function during cluster growth. Panels (a) and (b) show examples of the normalized scattering phase function for hexagonal and quadratic clusters, respectively. $D$ is the cluster size for incident wavelength $\lambda = 1.2$ mm, $N$ is the number of particles in cluster. The forward scattering peak values are presented on each phase function. Panels (c) and (d) demonstrate changes of the scattered radiation energy in main peaks and semiwidth of the forward scattering peak, respectively.
3. Radiation transfer in scattering layers of particle clusters

To analyze the multiple scattering in complex media with local order of scatterers, we consider a plane layer consisted of particle clusters, which scattering phase functions were studied in the previous section. We use Monte Carlo numerical approach [18] of solving radiation transfer equation [19–21] for finding angular distribution of the scattering radiation. Applying the second local estimation in MC algorithm [17], it is possible to find the scattered radiation from an isotropic source on a point detector, placed in the right layer border on the axis \((x = 0, y = 0, z = z_0)\).

We have done MC calculations for different layers made of different clusters shown in the figure 2. Our results demonstrate the correspondence between elongation of the forward scattering direction of phase function and the overall scattering distribution. Examples of scattered radiation distribution for small clusters are shown in figures 3(b) and (c). Secondary peaks of these distribution are well noticed, whereas for larger clusters they become smaller.

We also consider the case of scattering medium with various local orders, which corresponds to natural physical processes when different stages of particle clustering are presented simultaneously. We model such media by placing clusters of different size in one layer, as it is shown in the figure 3(d). MC results of radiation transfer in such layers are presented in the figures 3(e) and (f) for hexagonal and quadratic structures (red curves), respectively. Trying to find out, whether these distributions have any differences to the ones previously discussed, we receive the best match with scattered radiation distribution of the middle-size cluster layer (blue curves). We can notice that the main difference between them are in the forward scattered intensity.

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\begin{align*}
\text{Figures 3.} & \quad \text{MC calculation of the radiation transfer through scattering layers. Panel (a) shows the layer model consisted of single cluster type and MC computational parameters, } z_0 \text{ is the layer width, } N \text{ is the number of rays in MC algorithm, } \varepsilon \text{ is the extinction coefficient, } D \text{ is the cluster size, } \lambda \text{ is the radiation wavelength of point isotropic source. Panels (b) and (c) show angular distributions of the scattered radiation for layers of small clusters presented on the corresponding panels. Panel (d) demonstrates models of scattering layers consisted of different cluster types. Panels (e) and (f) show angular distributions of the scattered radiation for the layers from panel (d) (red curves) and layers made of middle-size clusters (blue curves).}
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Thus, we can replace the model of complex media by the middle-size simple model, unless we do not need to determine precisely forward scattering.

4. Conclusion
In the present paper we presented the numerical and analytical study of multiple scattering on the particle clusters. The results of growing cluster phase function showed the possibility of finding scattering characteristics only from local parameters. We have analyzed the scattered radiation in the complex media with local order consisted of particle clusters. Numerical computation of radiation transfer through such scattering layers shows the impact of local order on the angular distribution of scattered radiation. Moreover, we have studied the differences of the scattered radiation in media consisted of single- and mixed-type clusters. It is possible to substitute a set of different clusters by the middle-size one, but if the more accurate results need to be received, maximal amount of cluster types should be considered.

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