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DIFFUSION APPROXIMATION FOR MODELING OF 3-D RADIATION DISTRIBUTIONS

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RECENT PUBLICATIONS, SUBMITTALS FOR PUBLICATION AND PRESENTATIONS:

A) A. Zardecki, S. A. W. Gerstl, and J. F. Embury, "Imaging through a Multiple Scattering Medium." Proceedings of the 1984 CRDC Scientific Conference on Obscuration and Aerosol Research, Chem. Res. and Devel. Center report CRDC-SP-85007, 491-494, June 1985.

B) A. Zardecki, S. A. W. Gerstl, and J. F. Embury, "Multiple Scattering Effects in Spatial Frequency Filtering," Appl. Opt. 23, 4124-4131 (1984).

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H) R. L. Armstrong, S. A. W. Gerstl, and A. Zardecki, "Nonlinear Pulse Propagation in the Presence of Evaporating Aerosols," submitted to J Opt. Soc. Am., February 1985.

ABSTRACT

A three-dimensional transport code DIF3D, based on the diffusion approximation, is used to model the spatial distribution of radiation energy arising from volumetric isotropic sources. Future work will be concerned with the determination of irradiances and modeling of realistic scenarios relevant to the battlefield conditions.

INTRODUCTION

Light propagation through an optically thick particulate medium is basically a multiple-scattering problem in which rays or photons traverse a medium of scatterers and undergo many scattering events before escaping. A natural framework to deal with this type of problem is provided by the theory of radiative transfer The linear Boltzmann equation--in the context of radiative energy also termed the equation of transfer--governs the radiation field in a medium that absorbs, emits, and scatters radiation.[1]

The complexity of the equation of transfer forces one to implement numerical methods of solution. The most direct procedure is the discrete-ordinates approach, in which the radiance distribution function $I(\vec{r},\vec{\Omega},\lambda)$ is replaced by a discrete set of values at a discrete set of points $(\vec{r}_i,\vec{\Omega}_j,\lambda_k)$. Unfortunately, such a calculation becomes a rather formidable task even on the most powerful super computers available today.[2]

Because of the numerical complexities, an important aspect of transport theory involves the development of simpler approximate descriptions. There are some special cases where simple and useful solutions are available.[3] For isotropic scattering the irradiance distribution function can be represented as a sum of two terms, the residue term and the branch cut integration. If the particles are mostly scattering (albedo $\omega \to 1$) the residue term whose behavior is identical to a diffusion process dominates over the branch cut integration for optical depth greater than unity.[4]

In this paper, we employ the diffusion approximation to model the spatial distribution of radiative energy density due to a collection of volumetric, isotropic sources. After outlining the essence of the diffusion approximation and discussing the limits of its validity, we give numerical results in the form of 3-D isosurface plots, representing the surfaces of constant energy density. It will be shown that as the detector sensitivity decreases, the individual radiation sources cannot be spatially distinguished, thus leading to a false target effect.[5]

DIFFUSION APPROXIMATION

The diffusion approximation, which corresponds to the lowest-order truncation in the spherical harmonics expansion of the radiance distribution function, was employed by Tam and Zardecki[6] to examine the role of non-small-angle scattering for off-axis beam propagation. To gain insight into the approximation in question, we write the radiance distribution function for any given wavelength λ, whose index will be dropped, in the form

$$I(\vec{r},\vec{\Omega}) = \frac{1}{4\pi}\left[\rho(\vec{r}) + 3\vec{\Omega}\cdot\vec{J}(\vec{r})\right] \quad , \tag{1}$$

where $\vec{\Omega}$ is a unit direction vector, and where the function $\rho(\vec{r})$, proportional to the energy density, satisfies a diffusion equation

$$-\nabla D\nabla\rho + (\sigma_t - \sigma_s) = q_o \quad . \tag{2}$$

In Eq. (2), σ_t and σ_s denote the total extinction and scattering coefficients, and q_o is the isotropic source term. If $<\mu>$ denotes the mean cosine of the scattering angle, which can be identified with the asymmetry parameter g, then the diffusion coefficient D is given in terms of the transport coefficient

$$\sigma_{tr} = \sigma_t - \sigma_s<\mu> \quad , \tag{3}$$

as

$$D = \frac{1}{3\sigma_{tr}} \quad . \tag{4}$$

Eq. (2) should be solved with the boundary condition demanding that the radiant flux be directed inward and the scattering boundary be zero.

To delineate the range of validity of the diffusion approximation, we have compared the results for 1-D geometry obtained with the transport code ONEDANT[7] with the results obtained with the diffusion-based code DIF3D.[8] Figures (1) and (2) contain the results of computations referring to a 100 m wide slab, divided into 200 meshes of equal size. The isotropic source of unit strength, located in the first mesh with the boundaries 0. and 0.5 m generates the radiation field. As can be seen from Fig. 2, the diffusion theory leads to a degeneracy with respect to the single scattering albedo $\omega = \sigma_s/\sigma_t$. The perfect-scattering case, however, where $\omega = 1.0$, is described correctly within the diffusion approximation. This implies that the diffusion theory can be applied to model radiation distribution and multiple scattering in dense, non-absorbing media, such as inventory smokes in the visible range of the spectrum.

FALSE TARGET EFFECTS

In Ref. 5, we addressed the resolution problem that arises for a distant observer attempting to distinguish spatially between two thermal sources radiating into a turbid medium. Since our analysis was based on the transport theory, the results--especially for low optical depths--suffered from the ray effect distorting the spatial form of the radiation distribution. With the aid of the diffusion theory, we are in a position to entirely bypass the problem of ray effect; in addition the code DIF3D allows us to model 3-D situations, an unrealistic undertaking within the framework of the transport theory.

Our model scenario involves a cube 100x100x100 m in size. The lower half of the cube, $z < 50$, is filled with haze having the optical thickness 2.0 in the x or y direction. The upper half, $z > 50$, contains water cloud aerosol with optical thickness 8.0. Two isotropic point sources of equal strength located at $S_1 = (20,20,20,)$ and $S_2 = (80.80,80)$ produce the volumetric radiation distribution. By solving the diffusion equation (2) for ρ, we can compute the radiation energy density inside our scattering volume. For the wavelength of 0.55μm we show in Figs. 3 and 4 the isosurface plots representing surfaces of equal energy density. Choosing a fixed value for the maximum energy density, set by the source strength of the point sources, the resulting plots vary drastically with the value of the detectable energy density. Thus for a detector registering 4% or more of the maximum energy density the sources appear well separated, Fig. 3. On the other hand, for a detector registering 2% of the maximum energy distribution function, the individual sources appear to overlap, Fig. 4, leading to a false target effect. Similar results have been obtained with a larger number of sources both for homogeneous and inhomogeneous media.

CONCLUSIONS

Contrary to popular belief, the diffusion approximation is susceptible to yielding erroneous results when the single scattering albedo is smaller than 0.95. On the other hand, this approximation becomes a powerful tool to model complicated 3-D scenarios, which is today outside the scope of conventional approaches based on transport theory. Since diffusion theory does not deal with directional quantities, but with angle-integrated energy density, it does not suffer from the ray effect distortion. For these reasons, the false target problem finds a natural setting within the framework of the diffusion theory.

Our future investigation will largely focus on two as yet unsolved problems. First, using the diffusion approach, we intend to study the spatial detectability of radiating or reflecting objects placed in the vicinity of a smoke screen. When the radiation field is described in terms of irradiances, this becomes a problem of optical imaging. Second, to describe multiple scattering of laser beams in the off-axis regime, a novel approach valid for a wide range of size parameters needs to be formulated. A combination of the small-angle scattering approximation with diffusion theory should provide the desired computational base.

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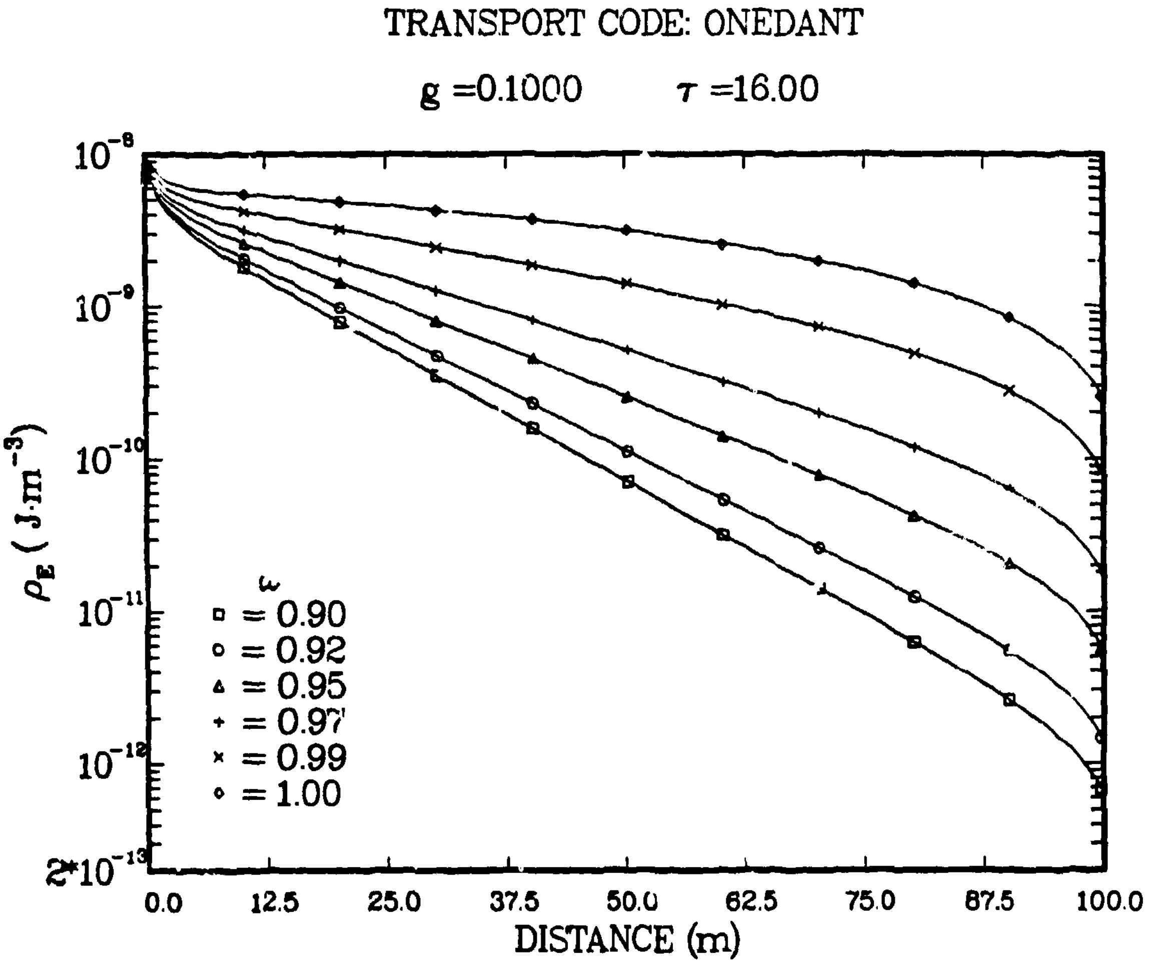

FIGURE 1. ENERGY DENSITY DISBRIBUTION PREDICTED BY TRANSPORT THEORY. Optical depth = 16, asymmetry parameter = 0.1.

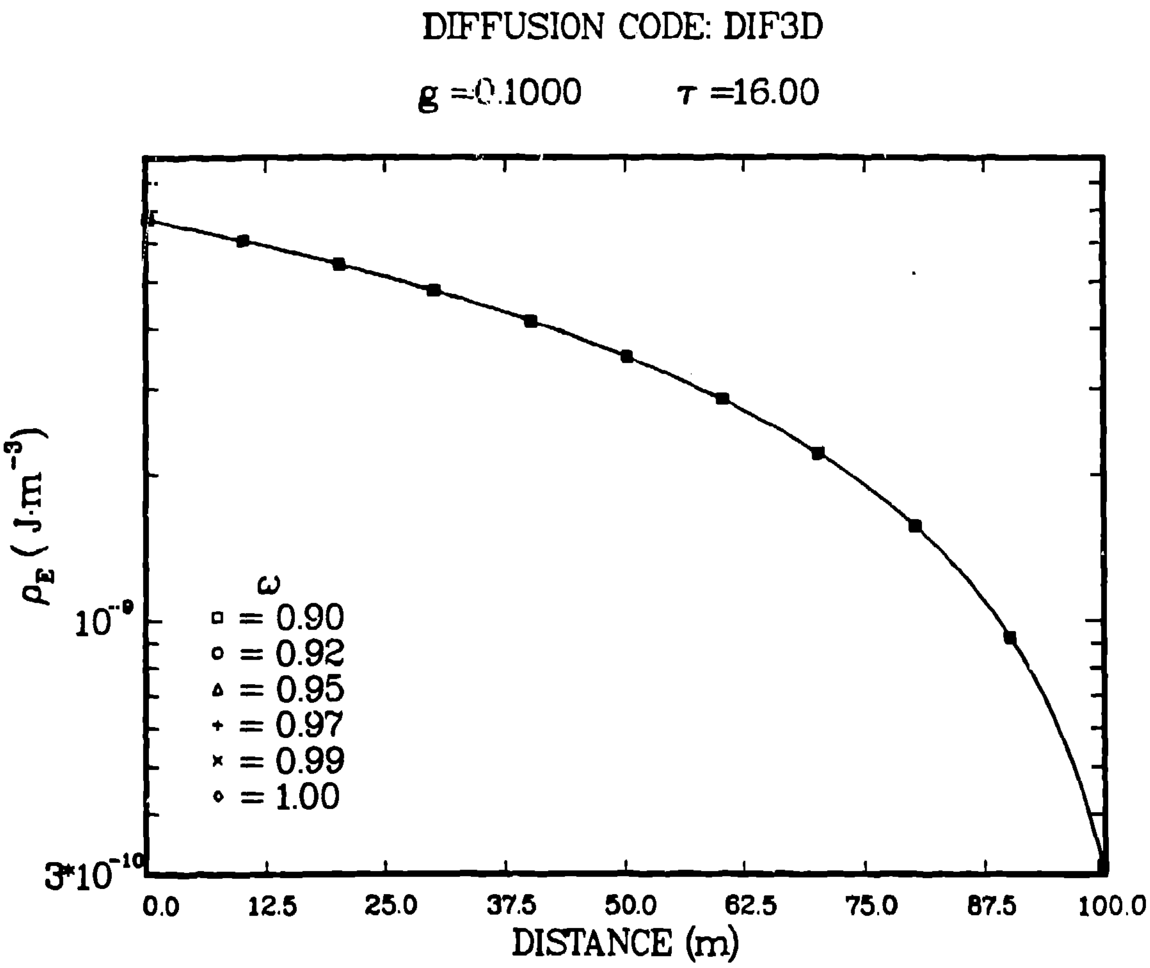

FIGURE 2. ENERGY DENSITY DISTRIBUTION PREDICTED BY DIFFUSION THEORY. Parameters as in Fig. 1. Note the degeneracy with respect to the single scattering albedo.

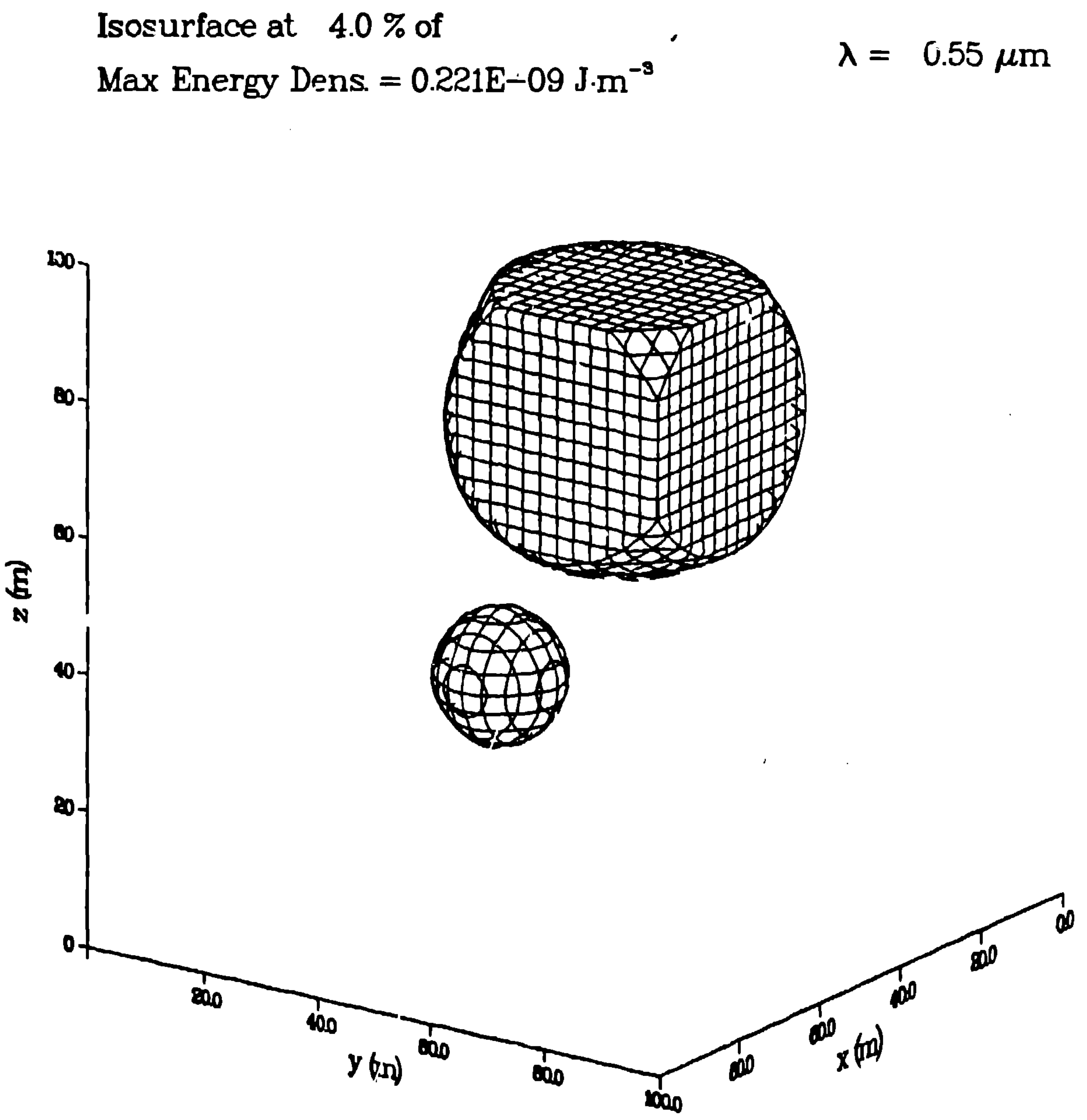

FIGURE 3. ISOSURFACE PLOT AT 4% OF MAXIMUM ENERGY DENSITY. Radiation fields from individual sources well separated.

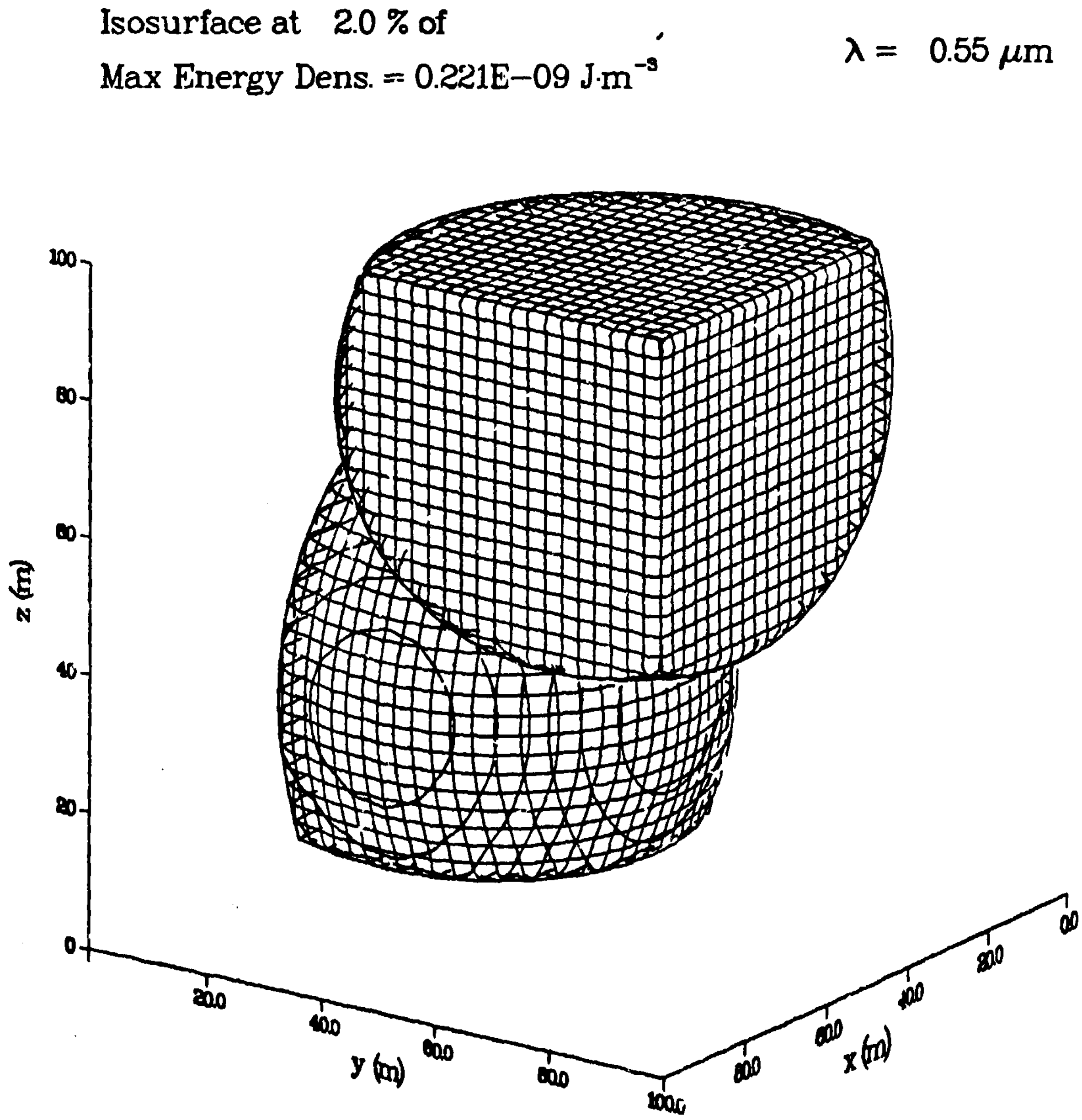

FIGURE 4. ISOSURFACE PLOT AT 2% OF MAXIMUM ENERGY DENSITY. Radiation fields from individual sources overlap, showing a false target effect.