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TITLE VAPORIZATION AND RECONDENSATION IN PROPAGATION AND IMAGING
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Vaporization and recondensation in propagation and imaging of laser beams

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ABSTRACT

To study the response of a medium to a localized disturbance, the coupled aerosol-beam equations—in which the dominant interactions are diffusive mass transport and conductive energy transport—are solved numerically, thus giving the spatio-temporal behavior of the propagating beam and the irradiated aerosols. In the context of the cloud clearing problem, a deleterious effect of recondensation is assessed. We examine the effect of turbulence on the distribution of droplet sizes during the recondensation. Results relevant to propagation and imaging are given.

1. INTRODUCTION

The propagation of high-energy laser (HEL) beams through the atmosphere is often dominated by interactions with atmospheric aerosols, which can scatter and absorb energy from the beam. Energy absorbed by the aerosols leads generally to an increase in aerosol temperature, to enhanced vaporization of the aerosol, and to an increase in conductive energy transfer from the aerosol to the ambient medium.¹ If energy is absorbed at a sufficiently high rate, a variety of HEL-related phenomena may occur. These include explosive vaporization, ablation of the aerosol material, shock wave formation in the ambient medium, and aerosol-induced plasma formation.²

In this paper, we focus on propagation and imaging through water clouds and fogs when an HEL beam first clears the aerosol cloud, to be subsequently degraded again by the process of recondensation. As we have indicated earlier,³ as the laser energy increases, the point spread function shows less and less broadening, the process termed HEL-assisted imaging. To study the response to a localized disturbance, the coupled aerosol-beam equations—in which the dominant interactions are diffusive mass transport and conductive energy transport—are solved numerically to obtain the spatio-temporal behavior of the propagating beam and the irradiated aerosols. In the frequency domain, a quantity analogous to the modulation transfer function of the linear regime⁴⁻¹⁰ is obtained.

In the case of pulsed radiation, the vaporized droplets will, by virtue of recondensation, grow appreciably on the time scale of seconds. From the standpoint of the cloud clearing this is a deleterious effect, which needs to be assessed. We examine the effect of turbulence within a cloud on the distribution of sizes of droplets growing by condensation. This is achieved by a numerical simulation of the fluctuating updraft velocity. As the droplets which experience a high supersaturation—and therefore grow rapidly—are likely to be in a strong updraft, they will spend only a relatively short time growing in size. This suggests that, as time goes on, the droplet size distribution will be characterized by low dispersions, a result confirmed by our simulation. Numerical results relevant to propagation and imaging will also be given. Typically, a HEL beam will punch through a cloud, whereas a low-energy probe beam will undergo the multiple scattering from the recondensing droplets which increase in size.

2. IMAGING THROUGH THE NONLINEAR MEDIUM

The time-dependent radiative transfer equation, written in the small-angle approximation, has the form

$$\left(\frac{\partial}{\partial z} + \phi \cdot \frac{\partial}{\partial \rho} + \sigma_t\right)I(\rho, z, \phi, t') = \sigma_s \int p(\phi - \phi')I(\rho, z, \phi', t')d^2\phi'. \quad (1)$$

In Eq. (1), $t' = t - z/c$ is the retarded time, the properties of the medium will, in general, be dependent on space and time.

The solution algorithm for Eq. (1) is given in Ref. 11. For the sake of completeness, we provide the final formulas for the laser flux (irradiance) in the case where the phase function is described by the Gaussian functional form

$$p(\phi) = \frac{\alpha^2}{\pi} \exp(-\alpha^2 \phi^2) \quad (2)$$

and where the pulse profile at $z = 0$ factorizes

$$I(\rho, z = 0, \phi, t) = I_0(\rho, \phi)T(t), \quad (3)$$

where the prime over t has been dropped. The small-angle approximation irradiance

$$F(\rho, z, \tau) = \int I(\rho, z, \phi, \tau)d^2\phi \quad (4)$$

is obtained by successively applying the formula

$$F(\rho, z + \Delta, \tau) = \frac{1}{(2\pi)^2} \exp[-\sigma_t(z, \tau)\Delta] \int G(\rho - \rho', z, \tau)F(\rho', z, \tau)d^2\rho' \quad (5)$$

Here Δ is a propagation distance satisfying the condition $\sigma_s \Delta \ll 1$, and the propagation kernel G is defined as

$$G(\rho, z, \tau) = \frac{1}{\pi} [K^{-1} \exp(-\rho^2/K) + \sigma_s \Delta L^{-1} \exp(-\rho^2/L)], \quad (6)$$

the parameters K and L are expressed in terms of α , the inverse angular spread of the phase function, and β , the inverse angular spread of the beam,¹¹ as

$$K(z) = 2z\Delta/\beta^2, \quad (7)$$

$$L(z) = 2z\Delta/\beta^2 + \Delta^2/\alpha^2 \quad (8)$$

In actual computations, the algorithm is further improved if we replace the values of σ_s , σ_t , and α by the actual values, induced by the spatial beam profile. We note that Eqs. (7) and (8) simplify in the limit of a collimated beam, when $\beta \rightarrow \infty$.

To illustrate the use of our algorithm, we choose the medium in the form of a 3 m wide slab initially filled with a monodisperse collection of 10 μm radius water droplets. The concentration of the droplets $n_d = 2 \times 10^4 \text{ cm}^{-3}$ corresponds to the optical depth $\tau = 4.6$ at the laser wavelength $\lambda = 3.8 \mu\text{m}$. The laser beam having the initial spot size of 0.2 cm propagates in the form of a pulse of 0.1 msec duration, with the peak value of the flux equal to $2.0 \times 10^5 \text{ W/cm}^2$. In Figs. 1 and 2, we show the spatio-temporal shape of the pulse for $\tau = 0$ (input plane) and $z = 2$ m. Figure 3 demonstrates the punch-through effect: the attenuation of the on-axis beam irradiance is much smaller than predicted by the Beer-Lambert law. As seen in Fig. 4, the modulation transfer function (MTF) rolls off less and less for larger distances of propagation: the effect we term HFL-assisted imaging.

Figure 1. Functional shape of the pulse in the input plane, $z = 0$. The independent variables are time t and radial distance r from the beam axis, the latter is denoted ρ in the text. Peak power $I_{MAX} = 2 \times 10^5 \text{ W/cm}^2$.

3. RECONDENSATION OF WATER VAPOR

The recondensation of water vapor is controlled by the supersaturation parameter $\sigma = p_v/p_s - 1$, where p_v is the partial pressure of water vapor at ambient conditions, whereas p_s is the saturation vapor pressure for water. By applying mass, momentum, and energy conservation to an adiabatically ascending parcel of air,¹² the set of equations relating the changes in temperature T , supersaturation σ , and water content w can be derived. If $u(t)$ denotes the instantaneous component of vertical velocity, the barometric equation is

$$\frac{dp}{dt} = -\frac{gm_a}{RT} u(t), \quad (9)$$

where g is the acceleration due to gravity, T is the absolute temperature, R is the gas constant, and m_a is the molecular weight of dry air. The remaining equations are

$$\frac{dT}{dt} = \frac{L}{c_{pa}} u = \frac{g}{c_{pa}} u(t), \quad (10)$$

$$\frac{d\sigma}{dt} = \frac{m_a g}{RL} \left[\frac{cL}{c_{pa}T} - 1 \right] u(t) = \left[\frac{m_v}{c_{pa}R} \left(\frac{L}{T} \right)^2 + \frac{p}{c p_s} \right] u \quad (11)$$

Here L is the latent heat of condensation, c_{pa} is the specific heat of dry air at constant pressure, and $c = m_v/m_a$ with m_v denoting the molecular weight of water vapor.

FIG. 2. Functional shape of the pulse shown in Fig. 1 at a distance $z = 2 \text{ m}$.

The rate of growth of a droplet of pure water of radius r is given by

$$\frac{dr}{dt} = \left[\frac{\sigma}{r} - \frac{2\gamma m_v}{\rho R T r^2} \right] / \left[\frac{L^2 m_v \rho}{K R T^2} + \frac{\rho R T}{D m_v p_s} \right] \quad (12)$$

In Eq. (12), σ is the surface tension of liquid water, ρ is the liquid water density, K is the thermal conductivity of air, and D is the diffusivity of water vapor in air. Writing $dr/dt = f(r, \sigma, p, T)$, we then have

$$u = \int_0^\infty 4\pi r^2 n(r) f(r, \sigma, p, T) dr, \quad (13)$$

where $n(r)dr$ is the number of droplets with radii between r and $r + dr$. If the droplets are all of the same size, Eq. (13) simplifies to give

$$u = 4\pi r^2 n f(r, \sigma, p, T), \quad (14)$$

where n is the total number of droplets per unit volume.

For homogeneous and stationary turbulence, one can simulate the turbulent updraft by writing $u(t)$ as

$$u(t) = u_0 + u \sigma_u, \quad (15)$$

where u is a random number drawn from a set which is normally distributed with a mean zero and unit variance (standard deviation), and where σ_u describes the strength of the velocity fluctuation.

Figure 3 Space-time dependence of the beam irradiance on axis for $F_{\text{max}} = 2 \times 10^5 \text{ W/cm}^2$

4. NUMERICAL RESULTS

We show, to begin with, the results of a numerical simulation relevant to a recondensing water cloud, whose size distribution is initially given by the modified gamma distribution with the mean radius of $5 \mu\text{m}$. We take the fluctuating vertical wind velocity to be characterized by $\sigma_w = 0.1 \text{ m/s}$. This results in the fluctuating velocity $u(t)$ as seen in Fig. 5. The actual size distribution evolves by a shift towards larger droplets, Fig. 6. While the mean droplet radius increases with time, the standard deviation becomes smaller and smaller, as illustrated in Fig. 7. Figure 8 shows the actual vertical location of the air parcel.

To couple the dynamics of the recondensation to the equation of transfer, we go to the monodisperse limit, given by Eq. (14). The vaporized environment of small droplets is produced by a beam with the peak flux of $2 \times 10^5 \text{ W/cm}^2$. Subsequently, a low energy probe beam propagates through the medium undergoing recondensation. Because the total number of droplets per unit volume is kept fixed, the optical depth of the medium increases with time due to the growing size of the droplets. This results in a highly asymmetric temporal pulse profile, shown in Fig. 9, in which there is more pulse attenuation for larger times. During recondensation, the HFI assisted imaging effect has become suppressed. This is seen in Fig. 10, in which the MFI does not experience an inversion with the distance of propagation.

Figure 4. MTF corresponding to the pulse of Fig. 1 computed for different path lengths.

5. CONCLUSIONS

We have analyzed in some detail the effect of HEL assisted imaging relevant in the context of the cloud clearing problem.³ For the peak fluxes of the order of 10^5 W/cm², the droplet vaporization is the dominant interaction mechanism between the laser beam and the medium, thus allowing us to focus on the effect of interest. The effect of turbulence within a cloud on the distribution of sizes of droplets growing by condensation has been examined with the aid of a scheme for simulating updraft velocity numerically. We find that the recondensation effect, having time scales of the order of seconds, will tend to suppress the HEL assisted imaging. The hitherto neglected effect of turbulent mixing, which brings in new particles from the surrounding cloud into the clear channel, will be a subject of further study.

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Figure 5. The fluctuating velocity of the air parcel (continuous line) and the super-saturation (dotted line) as functions of time.

MODIFIED GAMMA DISTRIBUTION
 $\sigma_0 = 0.1 \text{ m/s}$

Figure 6 The evolution of the size distribution of water droplets from the log normal distribution function

Figure 7 The mean radius (continuous line) and standard deviation (dotted line) as functions of time

Figure 8 The height of the air parcel as a function of time.

Figure 9 Space-time dependence of beam irradiance on z -axis for the low energy beam propagating through a recondensing water cloud

Figure 10 MTF for the low-energy beam propagating through a recondensing water cloud