Physics Letters A 377 (2013) 2598–2603

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

Effects of rocket engines on laser during lunar landing

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ARTICLE INFO

Article history:
Received 14 July 2013
Accepted 29 July 2013
Available online 6 August 2013
Communicated by F. Porcelli

Keywords:
Plume
Lunar landing
Infrared laser
Lidar

ABSTRACT

In the Chinese moon exploration project "ChangE-3", the laser telemeter and lidar are important equipments on the lunar landing vehicle. A low-thrust vernier rocket engine works during the soft landing, whose plume may influence on the laser equipments. An experiment has first been accomplished to evaluate the influence of the plume on the propagation characteristics of infrared laser under the vacuum condition. Combination with our theoretical analysis has given an appropriate assessment of the plume's effects on the infrared laser hence providing a valuable basis for the design of lunar landing systems.

In the Chinese moon exploration project "ChangE-3", the landing schedule includes speed-down, attitude adjustment, hovering, softlanding, free falling, and finally touchdown. As important testing equipments, a laser telemeter and a lidar are equipped on the lunar landing vehicle. During the soft landing procedure, the laser telemeter is used to measure the distance between the landing vehicle and the lunar surface and the lidar is used to reconstruct the three-dimensional profile of the landing area on the lunar surface, as shown in Fig. 1. The laser beams will pass through the plume of a low-thrust vernier rocket engine that is used to adjust the descending attitude and velocity of the landing vehicle. The height above the lunar surface is 100 m at the beginning of softlanding. The measure error brought by the plume cannot exceed 10 cm that corresponds to 10 cm optical path difference or 1 mrad (0.10/100) beam bend, otherwise it will probably lead to the failure of landing. The axes of the lidar and the plume are parallel, and the scanning angle range of the lidar is 60 degree. Hence the incident angle of the infrared laser beam emitting from lidar into the plume is between 0 and 30 degree. The fields of plume including density, temperature, pressure, gradient of refractive index, etc., will result in attenuation, phase shift, and bend of the infrared laser beam. These factors may influence on the performance of the laser equipment, which therefore need to be evaluated.

The relevant research began with the "Apollo" project of USA in 1960's. P. Molmud et al. evaluated the energetic attenuation and bend of laser beam under the vacuum condition, which were caused by the rocket plume, based on the simulation calculation [1,2]. However, they neither studied the plume-caused aberration of laser beam nor did experiments under vacuum condition. Theoretical and experimental studies of effects of jet engines' plumes on laser beams under the atmospheric condition have been conducted during the years [3–6]. The transmission characteristics of the laser passing through the plasma fields [7], atmospheric turbulence, low-pressure gases [8], and missile exhaust plumes [9], etc., were also studied. Nevertheless, theoretical analyses and experiments under vacuum conditions like lunar landing need different mathematical models and more complicated laboratorial systems, in which little progress has been made so far.

To assess the risk of lunar softlanding, a two-step numerical computation approach is presented. First, the internal field inside the astroengine was computed based on the solution of Navier–Stokes equation (NS) [10] with the axial symmetry difference algorithm, then chose the exit cross section of engine nozzle as the entrance condition of particles, and computed the external field of plume based on direct simulation Monte Carlo (DSMC), which used probabilistic (Monte Carlo) simulation to solve the Boltzmann equation for finite Knudsen number fluid flows [11]. Second, the angular beam deflection and the shift of optical length of the laser beam were computed based on the deduced distribution of refractive index and the Gladstone–Dale equation [12], and the attenuation of laser energy was computed based on the distribution of the extinction coefficient [13], which was deduced from the distributions of temperature, pressure and mass fractions of main components that were computed in the first step.

The low thrust of vernier rocket engine changes its thrust by the adjustment of the ratio of the oxidizing agent to the incendiary

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0375-9601/$ – see front matter
http://dx.doi.org/10.1016/j.physleta.2013.07.052

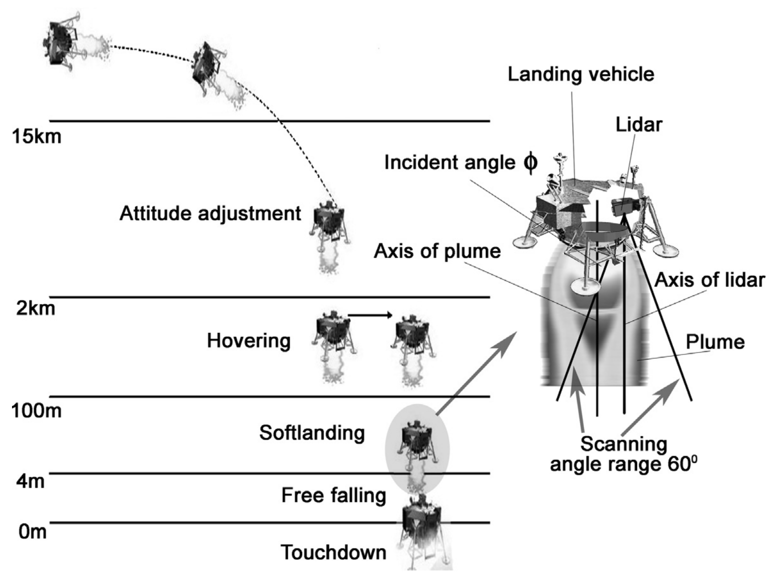

Fig. 1. Schematic of CE-3 lunar landing schedule and the interaction between laser beam of lidar and plume of astroengines.

agent and the combustion speed. The typical thrust ranges between 10 N and 150 N. Here we chose the parameters of 150 N thrust for the numerical computation. The main geometric parameters of the astroengine include the diameter of nozzle throat 11.7 mm and the diameter of nozzle exit 117 mm. The propellant consists of an incendiary agent monomethylhydrazine (mmh) and an oxidizing agent dinitrogen tetroxide (N_2O_4), where the ratio of N_2O_4 to mmh is 1.65.

The boundary condition and computational meshes of NS are shown in Fig. 2(a). The boundary condition of the entrance of engine nozzle can be obtained with the thermodynamic calculation under the working condition of 150 N thrust, which includes the total pressure 0.8 MPa, the total temperature 3045 K, etc.; supersonic speed was chosen as the boundary condition of the exit of engine nozzle; viscous no-slip boundary was chosen as the boundary condition of the inner wall surface of engine nozzle. The setup of computed region and the division of computed meshes are shown in Fig. 2(b). The distribution of the external plume field, including, stagnation temperature, density, and mass fractions of five main components computed with the axial symmetry DSMC is shown in Fig. 2(c)–(i).

The deflection of laser beam is associated with the distribution of the plume's refractive index that can be deduced from the distributions of the mass fraction of the ingredients of combustion resultant and the density of plume. The refractive index of plume composed of several constituents can be expressed as

$$n = 1 + \sum_i K_i \alpha_i \rho. \quad (1)$$

The distribution of α_i and ρ have been computed (Fig. 2(d)–(i)) and Gladstone–Dale constant [12] K_i of the five main components of plume are given in Table 1. The computed distribution of the refractive index of plume is shown in Fig. 3(a). Assuming that the transmitting distance of the laser beam through the plume is L, the components of the angular beam deflection in the s- and t-directions can be expressed as

$$\Delta\varphi_s = \int_0^L \frac{1}{n}\frac{\partial n}{\partial s}\,dl, \qquad \Delta\varphi_t = \int_0^L \frac{1}{n}\frac{\partial n}{\partial t}\,dl. \quad (2)$$

Three coplanar incident beams (incident angle $\varphi = 0°$, 45° and 90°, Fig. 3(a) that intersect with each other at the point ($x = 0.8$ m, $y = 1$ m) were chosen to compute the angular beam deflection and the results are shown in Table 2.

The measured distance L_m between the laser ranger or lidar and the object would be greater than the actual distance L_a due to the shift of optical length ΔL when the laser beam passes through the plume that has the distribution of refraction index larger than 1. The shift of optical length of the laser beam through the plume can be described as

$$\Delta L = \int_0^L n(l)\,dl - L, \quad (3)$$

which is the difference between the optical length and the transmitting distance of the laser beam through the plume and here the angular beam deflection must be considered for the integral path.

The same three coplanar incident beams were chosen to compute the shift of optical length and the results are also shown in Table 2.

The attenuation of laser energy is mainly due to the absorption and scattering of the molecules of gases in plume. The absorption coefficient of plume can be expressed as

$$\beta_a = \sum_i Q_i N_i, \quad (4)$$

where Q_i can be computed based on the distributions of temperature and pressure; N_i can be given by

$$N_i = \frac{\alpha_i \rho}{M_i} N_A. \quad (5)$$

The scattering coefficient of plume can be approximately expressed as

$$\beta_s = \frac{8\pi^3 (n^2-1)^2}{3N_A^2 \lambda^4} \sum_i N_i. \quad (6)$$

Here λ is 1064 nm. Then the extinction coefficient of plume is

$$\beta_e = \beta_a + \beta_s, \quad (7)$$

whose computed result is shown in Fig. 3(b). The energy attenuation of laser beam when passing through the plume can be expressed as