POTENTIAL OF LASER SENSING OF CIRCUMTERRESTRIAL SPACE

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Possibility of spaceborne lidar application to the exploration of circumterrestrial space has been analyzed. The optical characteristics of the principal light scattering constituents including molecules and atomic gases, free electrons, aerosols, and space debris have been evaluated at altitudes of 100–500 km *above the Earth's surface. The power of lidar return signals has been estimated based on the laser sensing and laser detection and ranging equations. It is shown that spaceborne lidar with modern technical characteristics is capable of reliable reception of signals from disperse components of circumterrestrial space at distances of several hundred meters from a spacecraft. Pieces of space debris can be detected by a lidar at distances from a few kilometers to several tens of kilometers.*

Methods of lidar investigation of the atmosphere have already been in use for solving pure scientific and applied problems. Moreover, spaceborne lidars have already been developed, and a lidar was used to perform the first experiments thus far.[1] However, in this case investigated objects – clouds and aerosols – were near the Earth's surface at distances no longer than several tens of kilometers.

At the same time vast circumterrestrial space exists in which numerous solar–terrestrial interactions are manifested and human activity takes place. Sporadic solar activity and regular motion of the terminator through the atmosphere engender various waves of lengths 130–520 km whose parameter variations reach 10–50% (see Ref. 2). Classical methods of radiophysics are capable only to monitor charged particles and are practically inapplicable to neutral atoms and molecules. The same is also true for space dust.[3] For these reasons, wide possibilities of laser radar application have opened here since they have much greater efficiency of interaction with the above–indicated particles.

In addition, the problem of space debris in circumterrestrial space comes into play. The remains of satellites, rocket carriers, products of incomplete and complete combustion of propellent, and, among other things, the wastes of human activity in space are referred to as space debris. Metal particles whose size is smaller than a few centimeters and dielectric particles cannot be detected by radars. Small pieces of debris are most massive pollutants of near space.[4]

In all the above enumerated cases a lidar placed on a stationary space platform or onboard patrol satellite orbiting at variable altitudes has much potential for exploration of natural and anthropogenic pollutants of circumterrestrial space.

In this paper, I make an effort to access the potential of a lidar of modern design at the present technology level. Elastic scattering is considered as basic physical phenomena. It exhibits maximum optical interaction cross section and yields good technical results.

An analysis of the available literature has revealed three basic natural light scattering components in the near circumterrestrial space. At altitudes up to 500–600 km, they are molecules and predominantly atoms of principal atmospheric gases, aerosols or, more correctly, space dust, and free electrons.

The vertical profile of free electron number density synthesized from published data was reported in Ref. 5. The cross section of photon scattering by free electrons being equal to $3\cdot10^{-25}$ cm^2 was also given there. In nonrelativistic case, it is independent of the optical radiation wavelength.

The vertical profile of the volume scattering coefficient σ_e calculated from these data is tabulated in Table I. At an altitude of about 300 km above Earth's surface, the volume scattering coefficient attains the maximum. Obviously this average profile will significantly change over the period of disturbed sun and other magneto–electric process.

TABLE I. Vertical profiles of the volume coefficient of scattering by free electrons σ_e*, space aerosols* σ_a*, and molecular–atomic mixture* σ_m*.*

Altitude, km	σ_e, m^{-1}	σ_a, m^{-1}	σ_m, m^{-1}
0	–	–	$1.34\cdot10^{-5}$
100	$6.5\cdot10^{-18}$	$2\cdot10^{-10}$	$3.8\cdot10^{-12}$
200	$1.3\cdot10^{-17}$	$1\cdot10^{-12}$	$4.8\cdot10^{-15}$
300	$2.6\cdot10^{-17}$	$3\cdot10^{-13}$	$1.5\cdot10^{-16}$
400	$2.0\cdot10^{-17}$	$6\cdot10^{-14}$	$1.3\cdot10^{-16}$
600	$6.5\cdot10^{-18}$	–	$5\cdot10^{-19}$

Aerosol origin, genesis, and distribution in the upper atmosphere – near cosmos – was analyzed in Ref. 3. It was shown that at altitudes above 140 km dust particle motion can be considered as free motion in the gravitational field of the Earth, i.e., only primordial space dust of arbitrary size entering the atmosphere without significant deceleration occurs at altitudes above 140 km. At altitudes below 100 km, only dust particles that have completely lost their initial space velocity may exist.

The vertical profile of the scattering coefficient σ_a derived in Refs. 6 and 7 is shown in Fig. 1. It was constructed from the atmospheric brightness observations in the wavelength range 300–1100 nm in the course of geophysical rocket launches neglecting the molecular scattering. It is interesting to note that at altitudes of 40 and 450 km the mean radius of dust particles was $\overline{r}$ = 0.2 μm, whereas their maximum radius r = 0.5 μm was observed within the 100–200 km altitude range.

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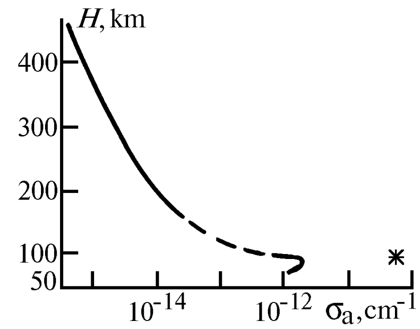

FIG. 1. Vertical profile of the aerosol scattering coefficient $\sigma_a(H)$ derived from the data of Refs. 6 and 7. Dashed portion of the curve shows the results of data interpolation. Asterisk denotes the data converted from Ref. 8.

A backscattering nephelometer with gallium arsenide diode lasers was launched on a geophysical rocket.[8] Layers of enhanced light scattering (their aerosol composition was supposed) were detected within the 9–110, 255–270, and 320–340 altitude ranges. The measured value of the backscattering coefficient of a 100 km layer was $7\cdot10^{-12}$ $cm^{-1}\cdot sr^{-1}$. In the assumption of the Rayleigh backscattering phase function (lidar ratio) being equal to 0.12 sr^{-1}, $\sigma_a = 5.8\cdot10^{-9}$ m^{-1}. The profile of the aerosol scattering coefficient constructed from the data of Ref. 6 and converted to a wavelength of 530 nm is also given in Table I.

As was pointed out in Ref. 3, aerosol light scattering coefficient may be smaller than the molecular one, that is, this parameter is variable as well. Evidently meteor showers entering the atmosphere play an important role. Relatively large meteors leave local trails whose optical characteristics may be calculated.[9]

Evaluation of the molecular scattering is most complicated in this problem. Indeed, there is canonical expression for the volume scattering coefficient of dust–free dry air at the wavelength λ

$$\sigma_m = \frac{8\pi^3\,(n^2-1)^2}{3\,N\,\lambda^4}\,, \tag{1}$$

where N is the number density of molecules and n is the refractive index of air.

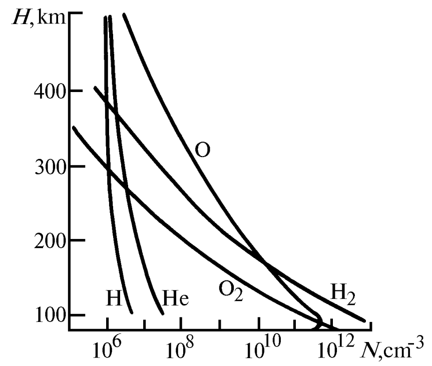

FIG. 2. Vertical profiles of the number density of atmospheric gases N(H) from Ref. 10.

The reference number densities of molecules of principal gases in the upper atmosphere are shown in Fig. 2 in accordance with the data published in Ref. 10. Quite significant variations in the number density of molecules are observed versus the time of the day, geographical latitude, and season. For example, half–year cycles are observed for atomic oxygen whose number density reduces to minima in summer and winter and reaches maxima in vernal and autumnal equinoxes.

The refractive index of atomic gases have not yet been measured because of the problem of their preparation. Therefore, their molecular values were taken as estimates, that is, n = 1.000 138 for hydrogen, 1.000 272 for oxygen, and 1.000 035 for helium. For air under normal conditions n = 1.000 292.

From formula (1), variation in the number density of molecules is accompanied with variation in the parameter $n^2 - 1$. On the basis of the Lorenz–Lorentz equation, expression

$$\sigma(H) = \sigma(H_0)\,\frac{\rho(H)}{\rho(H_0)} = \sigma(H_0)\,\frac{N(H)}{N(H_0)} \tag{2}$$

was recommended for use in Ref. 11, where $\rho(H)$ is the air pressure at altitude H. At the sea level, $N(H_0) = 2.687\cdot10^{-25}$ m^{-3} (see Ref. 12) and $\sigma(H_0) = 1.34\cdot10^{-5}$ m^{-1} for clear air at λ = 530 nm.

At the same time, the total number density of molecules decreases by nine orders of magnitude already at an altitude of 200 km, as is seen from Fig. 2. The average interatomic spacing becomes much greater than the sounding radiation wavelength, and cooperative effects become much less pronounced. Molecular scattering becomes true molecular rather than the scattering on fluctuations of the number density of molecules, and formula (1) describes exactly this case. Strictly speaking, in this case the notion of the refractive index loses its physical sense, and the problem of light scattering by a molecule or an atom should be considered from quantum–mechanical viewpoint. However, these data are lacking in the available literature, and in the first approximation it only remains for us to use the system of equations (1) and (2). The so–calculated coefficients of molecular scattering σ_m are also summarized in Table I. It should be noted, that the number density of molecules and σ_m are subject to variations of 50–100% of the given values according to the published data.

Quantum–mechanical approach was used by Grinberg[13] in examples of free radicals of radius of the order of 6Å. He pointed out that the effective absorption cross section is of the order of square diameter of particle. Absorption of light by an isolated small particle is accompanied with re–radiation of energy at the same frequency, with lifetime of the particle in the excited state being equal to 10^{-9} s. Here, we really are dealing with elastic scattering. Results published in Ref. 13 agree satisfactory with cosmogony hypotheses.

However, direct application of the above approach yielded obviously overestimated results. Thus, the scattering coefficient for atomic diameter of 0.4Å and the number density of atoms at an altitude of 100 km borrowed from Ref. 10 was equal to $1.2\cdot10^{-4}$ m^{-1} and exceeds even its value near the ground (see Table I). For this reason, based on general physical grounds, classical approach to molecular scattering was used in calculations.

Starting from the obtained estimates of light scattering ability of the upper atmosphere, the received signal power was calculated by the laser sensing equation for a spaceborne lidar. Applicability of the single–scattering approximation

$$P(r) = P_0\,S_0\,\eta\,\rho_0\,r^{-2}\,\beta_\pi\,\sigma(r)\,, \tag{3}$$

is beyond question here. In Eq. (3) $P(r)$ is the power received from the distance r, P_0 is the laser radiative power, S_0 is the aperture of a receiving telescope, η is the total efficiency of the entire optical train, $\sigma(r)$ is the scattering coefficient, β_π is the normalized backscattering phase function (lidar ratio), and ρ_0 is the laser pulse length. In its turn, $\rho_0 = c\tau/2$, where c is the velocity of light and τ is the pulse duration.

In calculations, the parameters $S_0 = 1$ m^2, $P_0 = 10^7$ W, $\eta = 0.5$, and $\rho_0 = 3$ m, that is, $\tau = 20$ns that are far from unique were used. For β_π, its value in the Rayleigh approximation being equal to 0.12 was used in all cases. To estimate the maximum value of the received signal power, r was taken 0.1 km. This value was large enough to eliminate the effect of the macroatmosphere surrounding a space platform with a lidar.[2] Table II summarized the results of calculation by Eq. (3). Each second column corresponding to a specific type of scattering indicates the number of the photons striking a photodetector for a lidar with a 100–250 m strobe length (that is, per 1 μs). The energy of each photon is $3.74\cdot10^{-13}$ J. An analysis of the obtained data indicates that short–range sensing of the above–considered atmospheric components is feasible. Within the 200–400 km altitude range typical for orbital stations it is quite possible by integrating the number of photons over several tens of laser shots to receive the signal power required for the determination of the atmospheric parameters.

TABLE II. Power P of a signal recorded by a lidar from circumsatellite space and the number p of photons received within a 1 μs strobe.

Altitude, km	Scattering by electrons		Scattering by aerosols		Molecular and atomic scattering	
	P_e, W	p_e	P_a, W	p_a	P_m, W	p_m
0	–	–	–	–	$2.4\cdot10^{-3}$	$3.9\cdot10^{9}$
100	$1.2\cdot10^{-16}$	$1.9\cdot10^{-2}$	$3.6\cdot10^{-8}$	$5.8\cdot10^{6}$	$6.8\cdot10^{-10}$	$1.1\cdot10^{5}$
200	$2.3\cdot10^{-15}$	$3.8\cdot10^{-1}$	$1.8\cdot10^{-10}$	$2.9\cdot10^{4}$	$8.6\cdot10^{-13}$	$1.4\cdot10^{2}$
300	$4.6\cdot10^{-15}$	$1.3\cdot10^{0}$	$5.4\cdot10^{-11}$	$8.7\cdot10^{3}$	$2.7\cdot10^{-14}$	$4.3\cdot10^{0}$
400	$3.6\cdot10^{-15}$	$5.6\cdot10^{-1}$	$1.1\cdot10^{-11}$	$1.7\cdot10^{3}$	$2.3\cdot10^{-15}$	$3.7\cdot10^{-1}$
600	$1.2\cdot10^{-16}$	$1.9\cdot10^{-2}$	–	–	$9\cdot10^{-17}$	$1.4\cdot10^{-2}$

It is interesting to note that within the 300–400 km altitude range light scattering by free electrons becomes comparable to the molecular scattering, whereas the aerosol scattering may be even stronger. Of course, it must be kept in mind that the values of these signals may change by 100%, whereas their aerosol component may change by two orders of magnitude due to instability of the upper atmosphere under conditions of meteor showers. Space dust is a natural integral part of space debris.

To evaluate the contribution from individual components of scattering, it is quite possible to use a multifrequency lidar, for example, with a Nd^{3+}:YAG laser generating fundamental, second, and third harmonics. It is well known that the molecular backscattering intensity is proportional to λ^{-4}, and the scattering by electrons is independent of the radiation wavelength in this spectral range. Models constructed on the basis of the exact Mie theory are applicable to sounding.

Here, no consideration has been given to the problem of background signal limiting the sensitivity of this method. Background signal comes from stars, emission of atmospheric gases, and scattered solar radiation. In the first approximation, emission spectra have no components at laser radiation wavelengths, and the lidar field of view may be directed away from the sources of background radiation, toward a lower level of background noise. This in no way affects exploration of circumterrestrial space.

After the problem of sensing of three–dimensional target, that is, the atmosphere, here we consider the problem of detection and ranging of two–dimensional targets, that is, large pieces of space debris.

In this case, lidar return signal obeys the equation of laser detection and ranging rather than the laser sensing equation. In accordance with Ref. 14, considering some salient features of lidar compared with radar, we obtain

$$P(r) = \frac{16\, P_0\, S_0\, \eta}{r^4\, \theta_0^2}\, \sigma_t\ , \tag{4}$$

where θ_0 is the angular beam divergence at the exit from a lidar and σ_t is the effective scattering cross section of an object being detected. This formula differs from the equation of lidar sensing, because the spatial length of a sensing pulse ρ_0 is omitted here. The lidar field–of–view angle is $\theta \geq \theta_0$.

The space debris has come under the scrutiny of science only in recent years. Nevertheless, an analysis of satellite damage and theoretical calculations relying on this analysis have shown that about $14\cdot10^6$ remains of satellites put in no catalog were orbited near the Earth at distances up to 2000 km by 1993. Their size varied from 1 to 15 cm (that is, they cannot be detected by ground–based radars). The space debris includes pieces whose size is larger than 0.1 mm (see Refs. 4, 15, and 16). As an illustration, the probability that an area of 1 m^2 of a spacecraft undergoes a collision with a piece of size larger than 0.1 mm over a 10–year period is 0.020, for pieces larger than 1 cm, it is equal to 0.000 32, and for pieces larger than 15 cm – 0.000 011 (see Ref. 4). The number density of these pieces is a function of the altitude of spacecraft orbit and its slope.

Metallic and plastic fragments, frozen propellant and oxidizer remains, and cosmonaut's waste products are known to be a part of these debris. Up to 60% of pieces have not yet been identified. Such uncertainty allows us to model these remains as Lambertian spheres to estimate their reflectivity and lidar detection potential in the first approximation.

For flat surface, the Lambertian phase function of reflection is $\cos\gamma/\pi$, where γ is the angle with the normal to the surface. By integrating over a hemisphere with the reflection coefficient q, it is not difficult to obtain their effective scattering cross section $\sigma_t = q\pi a^2/8$, where a is the diameter of the sphere, that is, the effective scattering cross section of a sphere is equal to half the geometric cross section.

By way of inversion of Eq. (4), we estimate the range of detection of these pieces. The technical parameters of a real laser altimeter placed onboard Russian geodetic satellite were used to estimate the threshold of single detection from a signal laser shot. The operation threshold of a photomultiplier of this altimeter (by the way, in the spare mode of operation) was $1.7\cdot10^{-8}$ W for an aperture of a receiving telescope of $5.7\cdot10^{-2}$ m^2. Conversion to a 1 m^2 aperture telescope yields $P_{th} = 9.7\cdot10^{-10}$ W.

In this case ranges of detection of isolated spheres 10.1 and 0.1 cm in diameters with the reflection coefficient $q = 0.5$ are 50.16 and 5 km, respectively. Recall that the background space radiation entering the receiving telescope of the lidar is not considered here.

Real pieces of space debris (aerosol debris) may be complex in shape and scattering phase function. They may have the complex refractive index, variable number density, and so on. This makes detection of space debris difficult and causes the use of several wavelength, luminescent and polarization analysis, and so on. Coherent lidars are alternative means for significant increase of the detection sensitivity. It may be suggested that lidars placed on a space sonde are capable to explore comet cores through comet gaseous–dust shells. In any case, the first steps in this direction have already been made in lidar sensing of lunar surface and lidar detection and ranging of asteroids.[18]

Thus, an orbital lidar harnessing elastic light scattering and having real technical characteristics is capable of exploration of circumterrestrial space not only from the standpoint of sensing of the number density of dust particles and gas molecules, but also from the standpoint of monitoring of negative consequences of human activity, namely, space debris.

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