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Modified View Factor Method for Estimating Molecular Backscattering Probability in Space Conditions

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Satellite contamination by backscattered molecules has been considered difficult to handle due to the strong directional anisotropy of the backscattering flux. Common analysis methods such as the Bhatnagar–Gross–Krook theory and the direct simulation Monte Carlo (DSMC) technique are rather inefficient in that they are complicated or take a long time for analysis. A new simple and easy-to-use technique of estimating the backscattering contamination is presented. This method is equivalent to the DSMC in so far as the molecular thermal velocity is much smaller than the satellite velocity and the mean free path for molecular collision is much longer than the satellite size. Based on the characteristics of backscattering seen from the satellite coordinate frame, backscattering is modeled as a diffuse reflection from a single hemispherical reflector, with the view factors modified by the direction cosine, and the effects of imperfect and distributed scattering are accounted for with proper correction factors.

Nomenclature

A	=	surface area
a, b, c	=	random coefficients used in Eq. (8)
$\mathrm{d}A$	=	area of the surface element
$\boldsymbol{e}$	=	directional unit vector in the x, y, and z directions
F_{ij}	=	view factor between surface i and j
g	=	relative velocity
g^*	=	relative velocity after collision
K_{back}	=	correction factor for imperfect backscattering
K_{dist}	=	correction factor for distributed collision
L	=	satellite characteristic size
m	=	mass
m_r	=	reduced mass
R	=	distance from the satellite
$\boldsymbol{r}$	=	unit vector in the direction of relative velocity after collision
U	=	random number
$\boldsymbol{V}$	=	velocity
$\boldsymbol{V}_m$	=	center-of-mass velocity
$\boldsymbol{V}^*$	=	postcollision velocity
$\boldsymbol{v}$	=	unit vector in the direction of $\boldsymbol{V}$
x, y, z	=	coordinates
λ	=	mean free path
θ	=	elevation or polar angle
φ	=	circumferential angle

I. Introduction

SATELLITES carry a variety of sensitive equipment such as solar arrays, mirrors, and lenses, whose performance is sensitively dependent on surface contamination, and in most cases, the performance of the optical equipment determines the overall performance of the satellite mission. Thus, an accurate estimation of contamination accumulation or the maximum contamination on sensitive surfaces during the satellite life is an essential issue in the design of a satellite.

Satellite contamination consists of particulate and molecular contamination. Particulate contamination occurs mostly on Earth or during launch, and most of the contamination on sensitive surfaces is molecular contamination accumulated on orbit. Naturally occurring molecules in the space environment are light molecules existing at very low concentration, so that their contribution to the permanent contamination on satellite is very small. Almost all of the contaminants on satellite surfaces originate from the satellite itself, either outgassed molecules from the surface or the effluents from vents and thrusters. Previous studies have confirmed that the thruster effluents rarely get attached permanently on the satellite surface, and permanent contaminants on satellite surfaces are mostly either outgassed molecules from satellite surfaces or effluents from vents.[1,2]

Because the mean free path for molecular collision is very long in most space conditions, molecules issuing from satellite surfaces or vents move along straight paths. When any of the surfaces face any of the contaminant sources, contaminant molecules will collide on these surfaces forming contamination layers. This is called the direct contamination, which is easily analyzed using the so-called view factors between surfaces, provided that the flux of contaminant molecules issuing from surfaces or vents is distributed to the isotropic cosine law. Because a satellite is usually designed so that view factors between sensitive surfaces and contaminant sources are kept to a minimum, most of the contaminant molecules first escape the satellite into space, but they collide with other molecules sooner or later, and some of them may return to the satellite, resulting in permanent contamination.

Predictions on the amount of contamination by backscattered molecules relative to the direct contamination vary widely from study to study. In fact the analysis of contamination by backscattering is quite difficult to handle because the backscattering phenomena occurring around a satellite moving at a very high velocity have a very strong anisotropy. Though the direct simulation Monte Carlo (DSMC) technique gives reasonable results by simulating the collision process with models physically similar to the real situation, it is quite inefficient, taking a very long time in computation. Also the entire computation has to be repeated all over again even with only a slight change in parameter values or conditions.[3–8]

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The objective of this study is to develop an easy and efficient method to calculate the backscattering contamination for satellites in space, under the assumptions that the satellite velocity is much higher than the molecular thermal velocity and the mean free path for molecular collision is much longer than the satellite size. These conditions are met with most of the satellites, except the lowest Earth orbit satellites below 400-km altitude. The basic features of the new method are similar to the conventional view factor, but the strong anisotropy of the backscattered molecular flux is properly taken into account through modifying the view factors in a systematic way. Therefore, once the modified view factor matrix, which is determined by the geometric factors alone, is obtained between various surface elements, the molecular exchange between surfaces can be easily calculated as with the conventional view factor method, even in the presence of parameter variations with materials, surface conditions, temperature, solar radiation intensity, and the like.

II. Formulation of the Modified View Factor Method

A. Basic Equations for Collision Between Contaminant and Ambient Molecules

Contaminant molecules issuing diffusely from satellite surfaces move into space with random thermal velocities relative to the satellite velocity, and the average vector velocity of the ambient molecules can be safely assumed to be zero. If viewed from a coordinate system fixed on the satellite (Fig. 1), the satellite remains stationary, outgassed contaminant molecules move radially outward from the satellite with an average thermal velocity $\boldsymbol{V}_1$, and ambient molecules approach the satellite with a uniform velocity $\boldsymbol{V}_2$, which is the satellite velocity measured from a coordinate fixed in space. Thermal motion of the ambient molecules can be neglected because it is usually much smaller compared to the satellite velocity. Contaminant molecules are assumed to have the same average velocity $\boldsymbol{V}_1$, which does not affect the derivation or the final result, and the directional distribution is assumed to follow the diffuse condition or the cosine law.

When two molecules of mass m_1 and m_2 have an elastic collision, postcollision velocities $\boldsymbol{V}_1^*$ and $\boldsymbol{V}_2^*$ can be written as follows:

$$\boldsymbol{V}_1^* = \boldsymbol{V}_m + (m_r/m_1)\boldsymbol{g}^* \tag{1}$$

$$\boldsymbol{V}_2^* = \boldsymbol{V}_m - (m_r/m_2)\boldsymbol{g}^* \tag{2}$$

Here $\boldsymbol{V}_m$ and m_r $[m_r = m_1 m_2/(m_1 + m_2)]$ are the center-of-mass velocity and reduced mass, respectively, and $\boldsymbol{g}^*$ is the relative velocity after collision, whose magnitude is conserved but direction varies with impact parameter in an elastic collision,

$$\boldsymbol{V}_m = (m_r/m_2)\boldsymbol{V}_1 + (m_r/m_1)\boldsymbol{V}_2 \tag{3}$$

$$g = g^* \tag{4}$$

In the extreme case of $V_1 \ll V_2$, relative velocity g or g^* is approximately equal to V_2, then Eq. (3) and Eq. (1) can be simplified as

$$\boldsymbol{V}_m \sim (m_r/m_1)\boldsymbol{V}_2 \tag{5}$$

$$\boldsymbol{V}_1^* \sim (\boldsymbol{v}_2 + \boldsymbol{r})(m_r/m_1)V_2 \tag{6}$$

In Eq. (6), $\boldsymbol{v}_2$ is the unit vector in the direction of $\boldsymbol{V}_2$, which is unidirectional in the $-z$ direction in this study and $\boldsymbol{r}$ the directional unit vector in the direction of relative velocity after collision.

In direct or Monte Carlo simulation of molecular motion, random parameter values are determined using random numbers. The angular direction is usually defined by the polar and circumferential angle as shown in Eq. (7). When the molecules are assumed as hard spheres, the direction of relative velocity after collision, $\boldsymbol{r}$, can be expressed as Eq. (8) based on the isotropicity of postcollision velocity in elastic collisions.[9] In the following equations U_1, U_2, U_3, and U_4 are random numbers:

$$\phi = 2\pi U_1, \qquad \theta = \cos^{-1}\left(\sqrt{U_2}\right) \tag{7}$$

$$\boldsymbol{\chi} = a\boldsymbol{e}_x + b\cos c\,\boldsymbol{e}_y + b\sin c\,\boldsymbol{e}_z$$

$$a = 1 - 2U_3, \qquad b = (1 - a^2)^{\frac{1}{2}}, \qquad c = 2\pi U_4 \tag{8}$$

B. Characteristics of Backscattering

As a first step to the understanding of backscattering contamination, the extreme case of $V_1 \ll V_2$ is examined first. In this extreme case, the z-directional velocity after collision can be written as Eq. (9). The value inside the first parenthesis of Eq. (9) is always negative or zero, implying that every contaminant molecule moves in the opposite direction to the satellite velocity after collision,

$$\boldsymbol{V}_{1z}^* = (-1 + b\sin c)(m_r/m_1)V_2\boldsymbol{e}_z \tag{9}$$

The directional distribution of $\boldsymbol{V}_1^*$ or the backscattered flux closely follows the cosine law, as is evident from Fig. 2. That is, in case of $V_1 \ll V_2$, the backscattering flux of contaminant molecules always has a random or cosine-law distribution about $-\boldsymbol{V}_2$, irrespective of the velocity and direction before collision.

When the condition $V_1 \ll V_2$ is not satisfied, that is, the molecular thermal velocity is not negligibly small compared to the satellite velocity, some of the contaminant molecules outgassed from the satellite into space may have a positive z component of $\boldsymbol{V}_1^*$. Then the directional distribution of the backscattered flux, which corresponds to the molecules with a negative component of $\boldsymbol{V}_{1z}^*$ may deviate from the diffuse or the cosine-law distribution. As is clear from Eq. (1) and Eq. (3), the probability of backscattering and the angular distribution of backscattered flux are dependent on three parameters, the mass ratio (m_1/m_2), the velocity ratio (V_1/V_2), and the collision angle. Figures 3 and 4 show the simulation results obtained for

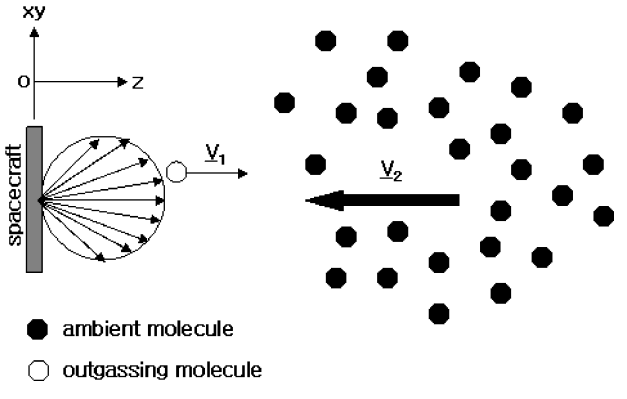

Fig. 1 Velocity vectors of outgassed and ambient molecules seen from satellite coordinate frame.

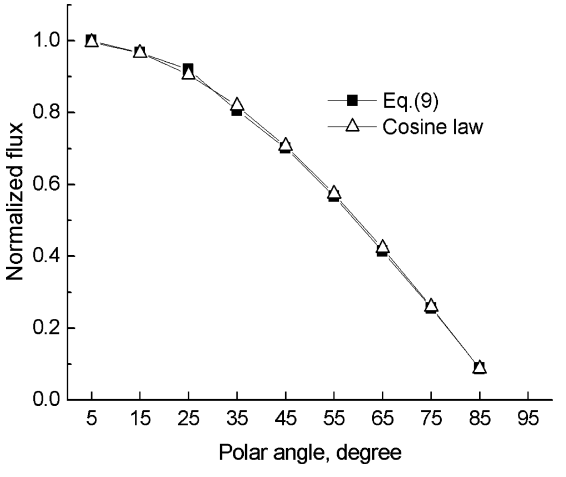

Fig. 2 Directional distribution of $\boldsymbol{V}_1^*$ for the extreme case of $V_1 \ll V_2$.

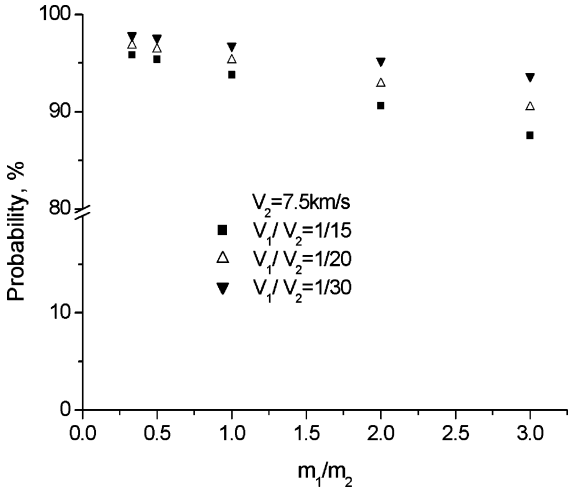

Fig. 3 Probability of backscattering after the first collision with ambient molecules.

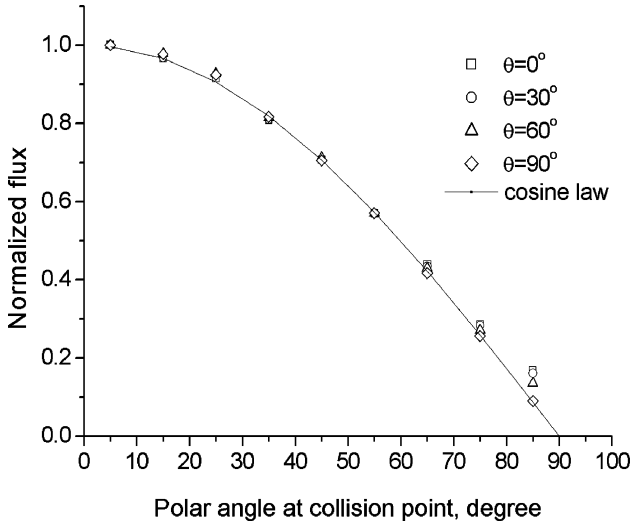

Fig. 4 Directional distribution of the backscattered flux: $V_2 = 7.5$ km/s, $V_1/V_2 = 1/20$, and $m_1/m_2 = 1$.

10^6 molecules with the mass ratio and the velocity ratio varied: $m_1/m_2 = 1/3$, 1/2, 1, 2, and 3 and $V_1/V_2 = 1/15$, 1/20, and 1/30.

The probability of backscattering, which is defined as the fraction of molecules having negative z component of $\boldsymbol{V}_1^*$ after collision, decreases with decreased mass of the ambient molecule or increased thermal velocity of the contaminant molecule (Fig. 3). However, it is higher than 80% over a very wide range of parameter values and is higher than 90% for typical conditions of medium-altitude satellites. Contaminant molecules moving in the normal (x or y) direction to the satellite velocity have a higher probability of escaping into space without backscattering, but the dependence on the collision angle is almost negligible (Fig. 4). The circumferential distribution of the backscattered flux should be uniform, which is confirmed by the direct simulation (Fig. 5). Variation of the backscattered flux with polar angle nearly follows the cosine law except that it is a little smaller than the cosine distribution near $\theta \sim 0$ deg and a little larger for the scattering into nearly normal directions to the satellite motion ($\theta \sim 90$ deg). However, the scattering in the normal direction does not contribute to the satellite contamination and also deviates very little from the cosine law (Fig. 4). Thus, it seems reasonable to assume that the directional distribution of backscattered flux follows the diffuse condition or the cosine-law about the satellite moving direction. In the extreme case of $V_1 \ll V_2$, the directional distribution is perfectly diffuse, which is evident from Eq. (6).

Because the backscattering probability does not depend on polar or circumferential angle, but only on the mass ratio and the velocity ratio, the analysis of contamination can be performed based on perfect backscattering and diffuse distribution, and then the effect of nonperfect backscattering has only to be corrected for by multiplying by the overall backscattering probability, K_{back}, which is a function of only the mass and the velocity ratio as is presented in Fig. 3.

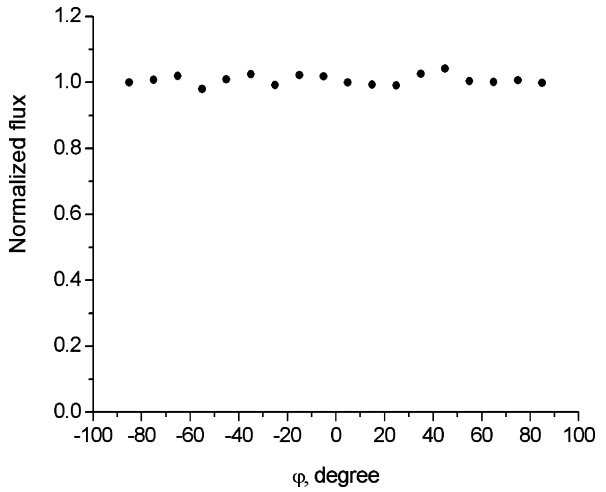

Fig. 5 Azimuthal variation of backscattered flux: $V_2 = 7.5$ km/s, $V_1/V_2 = 1/20$, and $m_1/m_2 = 1$.

C. Mass Transfer Equations Based on View Factors

As confirmed in the preceding section, contaminant molecules escaping the satellite into space collide with ambient molecules and get backscattered. When molecular thermal velocity is much smaller than the satellite velocity and contaminant molecule is not much heavier than the ambient molecule, which are the conditions typically found with most satellites, almost all of the molecules reverse their direction toward the satellite after a single collision with ambient molecules, and the directional distribution about the satellite moving direction closely follows the cosine law (Fig. 6). The characteristics of backscattering summarized above justify the use of view factors between properly defined surfaces for the analysis of molecular mass transfer.

Molecules collide at different positions or distances from the satellite, and the average distance from the satellite to the first collision is the mean free path λ. For typical satellite conditions, satellite size L is much smaller than $\lambda (L/\lambda \ll 1)$, and so multiple scattering can be safely neglected in the analysis. The analysis will first be performed for the simplified case of all of the molecules making collisions at λ, and then the effect of distributed collision distance will be considered later in the form of a correction factor.

When the backscattered flux has a cosine-law distribution about the satellite moving direction ($-z$ direction) and the backscattering probability is 1.0, the backscattering toward the satellite can be modeled as a reflection by a hemispherical reflector of radius λ (Fig. 7). A molecule escaping the satellite surface $\mathrm{d}A_s$ into a direction θ_2 makes a collision with the reflector and is backscattered. Because the reflected flux has to be diffusely distributed about the $-z$ axis, a perfectly diffuse reflector surface has to have its surface normal in the satellite moving ($-z$) direction, just like the surface element $\mathrm{d}A_2$ in Fig. 7, to reproduce correctly the distribution of backscattering flux. Then the hemispherical reflector has to consist of a number of flat vertical reflector elements along the hemispherical surface. Because scattering always makes molecules move in the $-z$ direction, the reflector elements are not needed to the left of the satellite position when calculating contamination. This kind of configuration with many separated elements is very complex and not easy to define and handle; thus, it would be better to use one smooth hemisphere as the reflector and modify the view factors instead. The modified reflector element on the hemispherical surface corresponding to $\mathrm{d}A_2$ is its projection on the hemispherical surface, $\mathrm{d}A_1 (\sim \mathrm{d}A_2 \cos\theta_2)$. Then

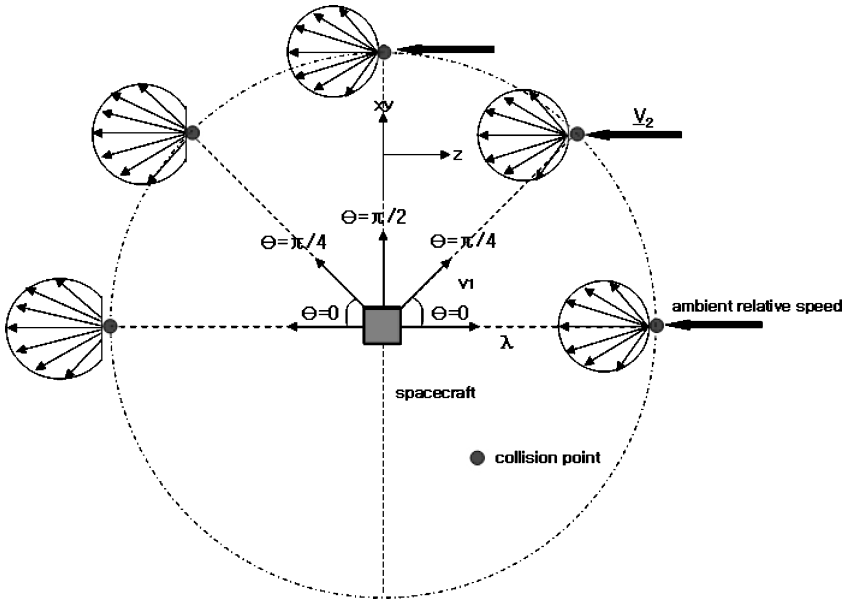

Fig. 6 Schematic of directional distribution of backscattering.

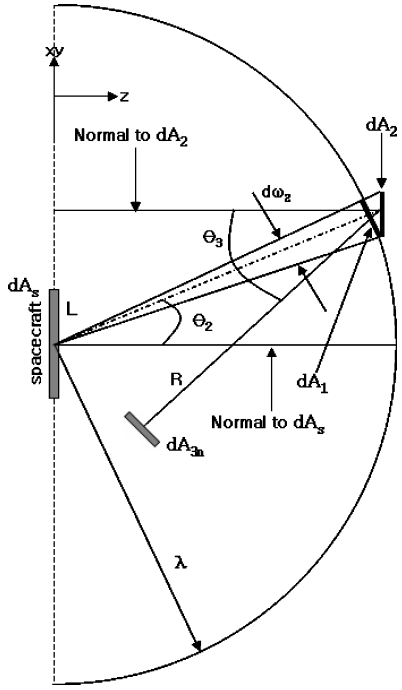

Fig. 7 Schematic of system used in modified view factor analysis for backscattering.

the solid angles subtended by these two surface elements from the satellite are equal, so that view factors for these two surface elements or the fractions of molecules from the satellite arriving at these two surfaces are equal. Although dA_s shown in Fig. 7 looks vertical, its facing direction is arbitrary in the following derivation.

Let dA_3 be another surface on the satellite on which backscattered molecules arrive to result in contamination. Then the fraction of the molecules starting from dA_s that arrive at dA_2 is the view factor F_{s2} between the two surfaces, and the fraction of the molecules reflected from dA_2 that finally return to dA_3 or dA_{3n} is F_{23}. Now the probability, F_{bs}, of a molecule starting from dA_s, reflected at dA_2 and finally returning to dA_3 or dA_{3n} can be written as[10]

$$F_{bs} = F_{s2} \cdot F_{2s} = F_{s2} \cdot F_{1s} \cdot \cos(\theta_2) \tag{10}$$

Two approximations, $\theta_2 \sim \theta_3$ and $R \sim \lambda$, are used in arriving at Eq. (10), based on the condition of $L/\lambda \ll 1$. Also used is the approximate relation, $dA_2 F_{23} = dA_1 F_{13}$, which is obtained when the reciprocity relation between view factors is combined with the approximate relationship $F_{31} = F_{32}$. Equation (10) shows that the overall contamination by backscattering can be calculated in terms of view factors between the satellite and the imaginary hemispherical reflector, if only the view factors viewing the satellite from the reflector surface at θ_2 are modified by multiplying the conventional view factors multiplied by $\cos(\theta_2)$. Once the view factors are determined, calculation of recontamination or mass transfer between satellite surfaces through backscattering can be easily performed by the standard procedures used with conventional view factors. The effect of imperfect backscattering can be easily accounted for, simply multiplying by the total backscattering probability, as was discussed in the preceding section.

D. Correction for the Distributed Collision

The formulations given earlier hold good for collisions made at a single distance from the satellite. In reality, molecules make first collisions at different positions or distances, so that the effect of the distributed collisions needs to be accounted for. According to kinetic theory, the probability of making a collision decreases exponentially with distance, and the average collision distance is λ. The probability of surviving without making a collision over a distance R, the survival probability P_s, is written as follows, and the probability of making a collision at R is the first derivative of the survival probability:

$$P_s = \exp[-(R/\lambda)] \tag{11}$$

To analyze the case of distributed collision, we can assume a series of hemispherical reflectors at different distances (Fig. 8). Then the overall backscattering contamination can be calculated as the sum, over each of the hemispherical reflectors, of the probability of making a collision at that reflector multiplied by the probability of returning to the satellite. What is sought is the ratio of the backscattering fluxes for the simultaneous collision at a single distance and for the distributed collisions, and the actual contamination in the presence of distributed collision can be easily found by multiplying the contamination for simultaneous collision by the ratio of fluxes. Thus, this ratio of fluxes is called the correction factor for distributed collision, K_{dist}. Because the characteristics of distributed collisions are the same at all angles, this ratio of fluxes does not vary at different angles, and the correction

factor for a specific direction is equal to that for the whole hemisphere. The ratio of fluxes between simultaneous and distributed collisions is derived for the whole hemispherical emission, and the source is taken as a disk of radius R_s on the frontal surface of the satellite.

For a specific reflector at distance R_i, the total area A_i is proportional to the square of the distance, $A_i \sim R_i^2$, and the probability of returning to the satellite after being reflected at this reflector is written as follows using the relationship between view factors:

$$F_{is} = (A_s/A_i) \cdot F_{si} = \tfrac{1}{2} \cdot (R_s/R_i)^2 \tag{12}$$

For collisions made very close to the satellite, $0 \le R_i \le R_0\ (=R_s)$, the returning probability can be safely assumed equal to 1.0, $F_{is} = 1.0$, because the fraction of close collision is quite small and $(R_0/\lambda) \ll 1$ in general. The average returning probability in the case of a distributed collision can be written as the integral of the product of the local returning probability, Eq. (12), and the collision probability at R, which is the first derivative of Eq. (11):

$$\begin{aligned}\bar{F} &= \int_0^\infty \frac{1}{2} \cdot \left(\frac{R_0}{R}\right)^2 \cdot \exp\left(-\frac{R}{\lambda}\right)\frac{\mathrm{d}R}{\lambda} \\ &= \sim \int_0^{R_0} \exp\left(-\frac{R}{\lambda}\right)\frac{\mathrm{d}R}{\lambda} + \int_{R_0}^\infty \frac{1}{2} \cdot \left(\frac{R_0}{R}\right)^2 \cdot \exp\left(-\frac{R}{\lambda}\right)\frac{\mathrm{d}R}{\lambda} \\ &= \sim \frac{R_0}{\lambda} + \int_{R_0}^\infty \frac{1}{2} \cdot \left(\frac{R_0}{R}\right)^2 \cdot \exp\left(-\frac{R}{\lambda}\right)\frac{\mathrm{d}R}{\lambda}\end{aligned} \tag{13}$$

When the integral of the first term in the second row of Eq. (13) is evaluated, the exponential function is replaced by a first-term approximation as $P_s = \exp[-(R/\lambda)] \simeq 1 - (R/\lambda)$, considering the condition $R_0 \ll \lambda$.

If the simultaneous reflector is at distance λ, the correction factor for the distributed collision can be written as follows, using the returning probability for the simultaneous collision for the hemisphere at λ, $F_{\lambda 0} = \frac{1}{2}(R_0/\lambda)^2$:

$$K_{\mathrm{dist}} = \frac{\bar{F}}{F_{\lambda 0}} = \left\{\left[\frac{R_0}{\lambda} + \int_{R_0}^\infty \frac{1}{2}\left(\frac{R_0}{R}\right)^2 \exp\left(-\frac{R}{\lambda}\right)\frac{\mathrm{d}R}{\lambda}\right]\Big/ \frac{1}{2}\left(\frac{R_0}{\lambda}\right)^2\right\} \tag{14}$$

Equation (14) clearly shows that the correction factor is dependent solely on the ratio of the satellite size and mean free path, R_0/λ, getting smaller as R_0/λ gets larger. Variation of the correction factor is shown in Fig. 9 for two different ranges of R_0/λ, and this result is universally correct.

The recontamination by backscattering in the presence of distributed collision/scattering is easily calculated by correcting the contamination obtained for a single reflector, $F_{\lambda 0}$, with K_{dist},

$$\bar{F} = K_{\mathrm{dist}} \cdot F_{\lambda 0} \tag{15}$$

Furthermore, the single reflector need not be located at λ but at any distance. If the single reflector is situated at distance R_a and view factors are defined for that reflector surfaces, even if the correction factor is given for a specific distance λ, the overall contamination can be obtained easily as follows, using the view factors for the reflector at R_a and the correction factor for a reflector at λ:

$$\begin{aligned}\bar{F} &= F_{\lambda 0} \cdot K_{\mathrm{dist}}(R_0/\lambda) = F_{R_{a0}} \cdot (F_{\lambda 0}/F_{R_{a0}}) \cdot K_{\mathrm{dist}}(R_0/\lambda) \\ &= F_{R_0} \cdot (\lambda/R_a) \cdot K_{\mathrm{dist}}(R_0/\lambda)\end{aligned} \tag{16}$$

When imperfect backscattering is considered, the overall backscattering probability K_{back} as is given in Fig. 3 has only to be multiplied.

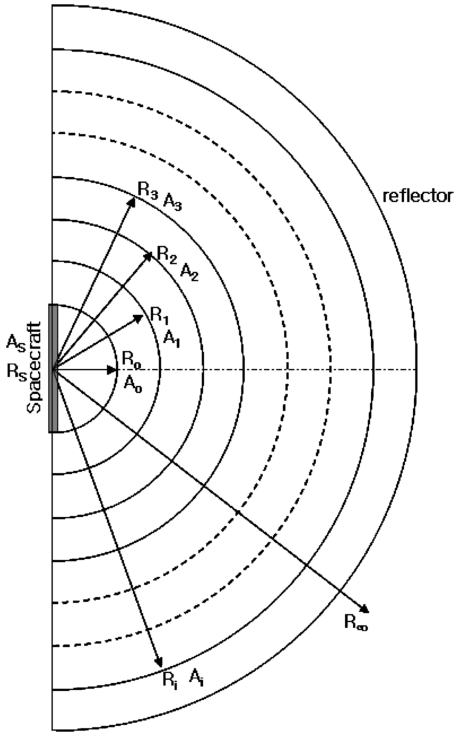

Fig. 8 Schematic for distributed collision.

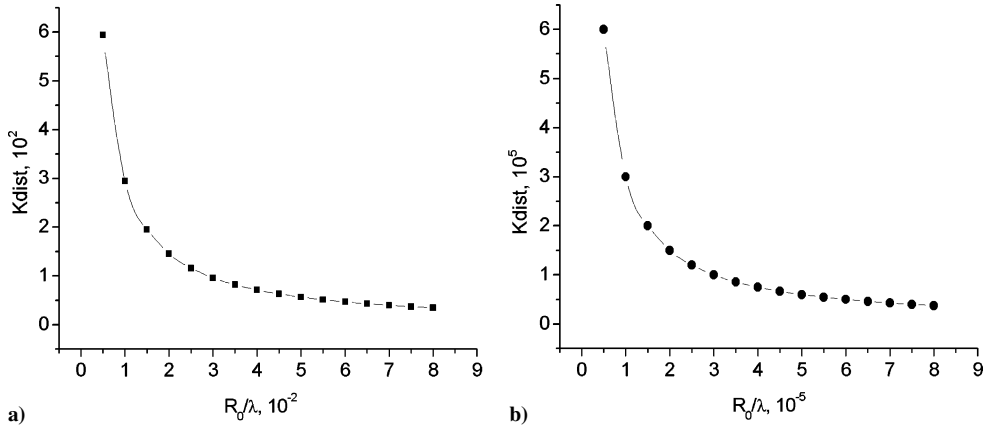

Fig. 9 Ratio of backscattering probabilities, K_{dist}, between simultaneous and distributed collision for two different R_0/λ ranges.

III. Conclusions

In typical conditions for satellites in space, the thermal velocity of the molecules is much lower than the satellite velocity, and the mean free path for molecular collision is much longer than the satellite size. Through a simple theoretical analysis on the elastic collision between hard spheres under these conditions, it is confirmed that contaminant molecules escaping a satellite are almost always backscattered with a probability close to 1.0 by just a single collision. With ambient molecules, and when viewed from a reference frame fixed on the satellite, the backscattering flux has a directional distribution closely following the diffuse condition or the cosine law about the satellite moving direction. These characteristics of backscattering justify the use of the view factor method, and a very simple method to calculate recontamination on a satellite by backscattering is formulated here, with only a slight modification to the standard view factor method.

In the new method, backscattering is modeled as a diffuse reflection from a hemispherical reflector of an arbitrary radius much larger than the satellite size. The satellite is at the center of the reflector, and the reflector covers only the half-space in the satellite moving direction. Then recontamination by backscattering on satellite surfaces can be calculated by the view factors between the satellite and the reflector surfaces, where the view factor viewing the satellite from the reflector are modified by the cosine of the direction angle of the surface element on the reflector. The effect of the distributed collision is accounted for by a correction factor, which is a function of just one parameter, the ratio of the satellite size, and the mean free path. The effect of imperfect backscattering can also be corrected for by simply multiplying by the total backscattering probability, which is a function of mass ratio and velocity ratio.

This method is simply an integrated expression of molecular collisions with the characteristic features made use of. Just as the standard view factor method is equivalent to DSMC in the absence of molecular collisions, this method is exactly equivalent to DSMC within the limitations of the simplifying assumptions. Because all of the assumptions used in the formulation are physically reasonable, the new method can be regarded to give results equivalent to the DSMC method. However, this method is much simpler and takes far less computation time. Also the variation of operational conditions, such as surface temperature, material/surface properties, and the like, can be easily analyzed, once the view factors are determined.

Because the derivations and the results are obtained under the assumption that satellite velocity and molecular mean free path are much larger than molecular thermal velocity and satellite size, respectively, the method and results will hold good for those conditions. However, these conditions are met with most satellites, except those on lowest Earth orbits.

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