Numerical analysis of ALADIN optics contamination due to outgassing of solar array materials

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Abstract. ALADIN is the very first space-based lidar that will provide global wind profile and a special attention has been paid to contamination of ALADIN optics. The paper presents a numerical approach, which is based on the direct simulation Monte Carlo method. The method allows one to accurately compute collisions between various species, in the case under consideration, free-stream flow and outgassing from solar array materials. The collisions create a contamination flux onto the optics despite there is no line-of-sight from the solar arrays to the optics. Comparison of obtained results with a simple analytical model prediction shows that the analytical model underpredicts mass fluxes.

1. Introduction
The Atmospheric Laser Doppler Lidar Instrument (ALADIN) is the only instrument on board of the ADM-Aeolus satellite, which will provide a global observation of three-dimensional wind fields over the Earth’s surface. ALADIN is based on a Nd:YAG laser, which generates 120 mJ pulses in the UV. The optical power in each pulse is about 5 MW \cite{1}. The received light is collected by a 1.5 diameter telescope and is transferred to transmit/receiver optics (TRO). The operation of a satellite in orbit creates a satellite atmosphere due to outgassing, thruster firings, leakage etc. This can contaminate sensitive surfaces and affect the life time of the instruments. Density, pressure, and species composition of this atmosphere differ significantly from hard vacuum properties. It is difficult to model the atmosphere in ground facilities and therefore a numerical simulation has been used to provide a contamination prediction. There is a serious concern of contamination of the primary and secondary mirrors, TRO, and power laser head (PLH) due to the phenomenon of laser induced contamination. Various sources of contamination of the mirrors, TRO have been checked: outgassing from solar array materials and from an internal surface of the telescope baffle, a contamination of the PLH due to influx of outgassing and thruster firing products through a purging system \cite{2}. The latter was performed using results from a thruster plume analysis \cite{3}. A conductivity of the purging system, which consists of tubes with a length of 250-1000 mm and internal diameter of 4-11.6 mm, was computed for different species and values of sticking coefficient \cite{4}. The current paper presents only contamination analysis performed for solar array material outgassing. Numerical results are obtained with the direct simulation Monte Carlo (DSMC) method \cite{5} and compared with an analytical model prediction.

2. Geometry and flow properties
The geometry of the satellite is shown on Figure 1. Solar arrays have a span of 13 meters. The mirrors are located inside the telescope baffle and there is no line-of-sight between the mirrors and solar arrays. The diameters of the primary and secondary mirrors are 1500 mm and 64.8 mm, respectively. The primary mirror has a hole in the center to transmit the laser pulse to the Earth’s atmosphere and receive the backscattered light, via the TRO. The hole has a diameter of 60 mm and length of 22 mm. Locations and geometries of these elements are shown in \cite{1}.
Figure 1. Water vapor mass flux over satellite surface without (left) and with (right) an interaction with free-stream (values in kg/m²/sec, time of 20 min)

It is assumed that free-stream flow consists of atomic oxygen only and its parameters at an altitude of 400 km are taken for ultra-high solar activity case. The density of the flow is equal to $3.3430 \times 10^{-11}$ kg/m³ for a point with maximum temperature, 2400 K, on one day orbits of Aeolus satellite. Table 1 lists four materials, which generate an outgassing flow from the solar arrays. Their masses are 3.0, 0.6, 2.7, and 0.6 kg, respectively. An outgassing rate is calculated with the following model for the total mass lost, $W_T$ [8].

$$W_T = \sum_{i=0}^{5} W_i \times (1 - \exp^{-t/\tau_i}), \quad \tau_i = \bar{\tau}_i e^{-K_e(T - T_{ref})}$$

where $t$ is time in hours, $W_i$ and $\bar{\tau}_i$ are the mass loss and time constants for a specific material, $T$ is a surface temperature, $T_{ref} = 25$ C, $K_e = 0.14, 0.13, 0.052$, and 0.139 for these materials, respectively. To calculate the outgassing rate, the following simplifications are used: (i) outgassing occurs from a back side of the solar array panels, (ii) outgassing is uniform from a surface of each solar array panel, (iii) it is assumed that outgassing species is water vapor within the first month in a space. Then outgassing is a species with molar mass of 200 g/mole and after three months the outgassing species has a molar mass of 484 g/mole, (iv) temperature of the solar array surface is modelled to be 90 C.

Table 1. Parameters for outgassing model

| Material | $W_0$ | $\bar{\tau}_0$ | $W_1$ | $\bar{\tau}_1$ | $W_2$ | $\bar{\tau}_2$ | $W_3$ | $\bar{\tau}_3$ | $W_4$ | $\bar{\tau}_4$ | $W_5$ | $\bar{\tau}_5$ |
|----------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|-------|----------------|
| PCBE     | 0.13  | 1.0           | 4.5e-2| 50             | 1.0e3 | 6.0e-2         | 2.0e4 | 0.13           | 2.0e6 |
| DC93500  | 0.20  | 0.12          | 3.3e-2| 25             | 4.3e-2| 8.4e2          | 4.5e-2| 2.2e4          | 5.9e-2| 5.6e5          | 0.22  | 1.8e7         |
| RTVS691  | 3.2e-3| 0.2           | 1.4e-2| 2.0e1          | 3.8e-2| 2.0e1          | 4.1e-2| 5.0e2          | 3.6e-2| 2.0e3          | 0.74  | 2.0e4         |
| CV1142   | 0.131 | 1.0           | 4.5e-2| 50             | 0.132 | 1.0e3          | 6.0e-2| 2.0e4          | 0.133 | 2.0e6         |

3. Numerical approach

Computations were performed with DSMC-based software, SMILE [6]. The DSMC method has become de facto, the main numerical tool of rarefied gas dynamics and it allows one to model molecular collisions accurately. For example, DSMC analysis performed for the UARS/HALOE telescope showed lower contamination than MOLFLUX analysis, and this was corroborated with on-orbit measurements [7]. DSMC computations are time-consuming due to the complex geometry of the Aeolus satellite, the three-dimensional nature of the interaction between free-stream and outgassing flows, and the large difference in spatial scales. For example, the size of
computational domain has to be up to 1500 meters to predict return fluxes accurately when the size of the hole is 0.06 m. To perform the analysis using a desktop computer, the computations have been conducted in the following two steps: (i) computation of three-dimensional flow around the Aeolus satellite, (ii) three-dimensional computation of a flow inside the telescope baffle.

To obtain the flow properties at the baffle entrance, a transmittable surface was placed there and a technique [9] was implemented to sample flow properties within small triangle elements, which together constitutes the surface. For the second step computation, properties of molecules entering the baffle were sampled with an ellipsoidal Maxwellian distribution function. The function uses different values of temperature in normal and two tangential directions to the surface of each triangle. This technique allows one to keep a flow thermal nonequilibrium and avoid the creation of large files with properties of molecules entering the baffle during the first step computation. Actually, an exact knowledge on the distribution function is not necessary because most of the molecules collide with the baffle surface in the first instance, then reflect diffusively. SMILE was updated to perform computations with a double precision to increase the solution accuracy.

It is assumed that Aeolus satellite surface has a constant temperature of 300 K except for the solar arrays. The value of the sticking coefficient is zero for all species because of the long time duration considered. A diffuse reflection model with complete energy accommodation is used to model the gas/surface interaction.

4. Results

Figure 2 depicts the density of water vapor and atomic oxygen around Aeolus satellite. Water vapor expands freely except in the case of the baffle disturbance. The density of atomic oxygen increases in the ram direction of the satellite significantly, and reduces to near zero in the satellite wake. The molecular velocity of free-stream and outgassing flows can differ from the bulk velocity significantly, therefore, such a flow can not be characterized by a single value of a molecular mean free path, $\lambda$. Figure 3 shows a mean free path of water molecule due to collisions with water vapor, $\lambda_{WW}$, and atomic oxygen, $\lambda_{WO}$. $\lambda_{WW}$ increases from 70 m at the solar array surface up to 4000 m in the vicinity of the baffle entrance. A value of $\lambda_{WO}$ is significantly smaller (about 200 meters at the entrance) and depends on molecular properties of the outgassing species and not on outgassing rate. Therefore, computations were performed for the few values of elapsed time with the above-mentioned outgassing species. Relationships between mass fluxes on the optics and outgassing rates were obtained in order to calculate a mass load over the lifetime of the satellite.

Figure 2. Number density of outgassing flow (left, 20 min) and atomic oxygen flow (right, values in $\#/m^3$)

Mass fluxes over the satellite surface are shown in Figure 1 at time of 20 min in space. The
outgassing flow is still relatively dense and collisions between water molecules can create return fluxes onto the solar arrays when the mass flux at the baffle entrance is negligible. An interaction between the outgassing and free-stream flows increases the return fluxes by a factor of 2-3 onto the solar arrays, and by an order of magnitude into the baffle entrance. Table 2 lists mass fluxes through the telescope baffle entrance for the few values of elapsed time obtained with the DSMC method, and an analytical model of satellite contamination [10]. The model calculates a backscattering flux for the satellite with a spherical shape. To apply the model, a sphere with a radius of 1.43 m was used, assuming that outgassing occurs from a half of the sphere surface and the outgassing surface is equal to the area of the solar arrays. In this case, the analytical model underpredicts the mass flux.

Figure 3. Mean free path of the water molecule in water vapor (left) and in atomic oxygen (right, values in m)

Table 2. Mass fluxes through the baffle entrance (values in kg/sec)

| elapsed time | DSMC     | model[10] |
|--------------|----------|-----------|
| 20 min       | 6.04e-11 | 4.57e-11  |
| 1 hour       | 1.48e-11 | 1.15e-11  |
| 5 days       | 5.87e-13 | 4.52e-13  |
| 30 days      | 3.86e-13 | 3.51e-13  |
| 1 year       | 1.21e-13 | 4.67e-14  |

5. Conclusions
An analysis of outgassing and free-stream flows around the Aeolus satellite has been performed with the DSMC method. The method allows one to accurately compute molecular collisions, which create a return flux, and the component of the solar array outgassing that can contaminate the ALADIN optics located inside the telescope baffle. DSMC-based software, SMILE, was modified to perform computations using a desktop computer and obtain mass fluxes over the satellite life time. A comparison of DSMC results for the mass fluxes through the baffle entrance with a simple analytical model prediction, shows that the analytical model underpredicts the fluxes.

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