

Dust impact and attitude analysis for JAXA's probe on the Comet Interceptor mission

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Abstract

Comet Interceptor (Comet-I), to be launched in 2029 as a piggyback to ESA's ARIEL mission, is aimed to perform the first fly-by of a pristine long-period comet. The mission will be composed of a main spacecraft, SC A (ESA), and two small probes to be released prior to the fly-by, SC B1 (JAXA) and SC B2 (ESA). This work analyzes the attitude performance of JAXA's 24U-sized spacecraft through the dust environment of a yet-to-be-discovered target comet. Main challenges to the mission are associated to the high levels of uncertainty and extremity of fly-by conditions: highly-active dust environment, uncertain fly-by altitude (750 ± 250 km (1σ), as of 2021), and large and unknown relative fly-by speeds (15–70 km/s). A Monte Carlo analysis is performed to characterize the effect of dust particle impacts on the attitude of SC B1, and to evaluate the likelihood of satisfying pointing and angular velocity requirements of the science camera. Analysis initially shows that particles of mass 10^{-8} – 10^{-5} kg represent the most relevant source of perturbation due to their transferred angular momentum and likelihood of being encountered, and saturation of reaction wheels is shown unlikely given the large fly-by speeds and short fly-by durations (20 min–2 h). More detailed analysis ultimately suggests a probability larger than 90% of satisfying science camera requirements despite the extreme, uncertain fly-by conditions, dust environment, and component inaccuracies (star tracker, gyroscopes, and reaction wheels). Results also show that upgrading the reaction wheel that is implemented along the camera line-of-sight can improve, but only marginally, attitude performance, and proper alignment of solar arrays parallel to the incoming flow of particles is shown essential to maximize probability of success.

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Keywords: Long-period comet; System requirements; Monte Carlo analysis

1. Introduction

Comet Interceptor (Comet-I) (Snodgrass and Jones, 2019) was selected in 2019 as the first fast-class ESA mission, to be carried as a piggyback to the ARIEL mission in 2029. Comet-I is an 850-kg mission (ESA-JAXA collab-

oration) aimed to perform the first fly-by of a pristine long-period comet, to be discovered soon after it first enters the inner Solar System. The mission is composed of a main spacecraft, SC A, which will orbit around the second Sun-Earth Lagrange point until a reachable long-period comet is discovered (Sánchez et al., 2021), and of two small probes, SC B1 and SC B2, to be deployed soon before the fly-by. Spacecraft SC B1, of 30 kg in mass and dimensions of a 24U CubeSat, will be developed by JAXA (JAXA Comet Interceptor Team, 2021) and is the focus of this study.

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Comet-I will face unprecedented challenges due to the type of target object: an *a priori* unknown, fast-moving comet (15–70 km/s) with highly-active and uncertain dust environment (since the comet is interacting with the Sun for the first time). The design and development of the mission shall also be carried out in the context of such uncertain and extreme conditions, and this study aims to characterize the attitude performance of SC B1 as it flies through the dust environment of the target comet. The probability of fulfilling attitude requirements during the science phase of the mission is evaluated, the effect of dust particle impacts on attitude performance is analyzed, along with the effect of solar array orientation and impact model validity, and recommendations for selection of control gains and sizing of reaction wheels are finally made in support of JAXA's SC B1 design and development.

Analysis of debris and dust particle impacts is an active field of research in the community, whose primary applications are low-Earth orbit (Institute of Space Systems, 2020; Sagnières and Sharf, 2017), interplanetary missions (Krüger et al., 2021; Putzar et al., 2019), planetary rings (Lee, 2016), and fly-bys of or close-proximity operations around asteroids and comets (Lisse et al., 2022; Moretto and McMahon, 2020; Rembor, 1993). Due to the novelty of the Comet-I scenario, however, new efforts have been devoted to model the cometary dust environment along the trajectories of the three spacecraft (Comet-I Dust Hazard Assessment Team, 2021), to provide a simplified numerical model for the attitude perturbation on ESA's SC A due to particle impacts (Haslebacher et al., 2022), and to develop an optimal attitude control algorithm for SC A to recover science time after a single large particle impact (Preda et al., 2022).

Alongside such efforts, this paper provides the first detailed, high-fidelity attitude performance analysis for JAXA's 24U probe in the Comet Interceptor mission. The simulation framework combines the dust environment model developed by the Comet-I Dust Hazard Assessment Team, a three-dimensional model of the spacecraft configuration, realistic modeling of the momentum transfer (including potential momentum enhancements due to hypervelocity impacts), best-current-knowledge performance of spacecraft components, etc. Given the largely stochastic nature of the problem, a Monte Carlo analysis is performed to statistically characterize the attitude performance of SC B1. Such analysis randomizes mission parameters and environment variables such as the fly-by altitude, fly-by speed, dust environment density and distribution, and component inaccuracies. Results then allow to assess the probability of success of the mission and provide insights into the effect of dust particles depending on their size, attitude performance depending on fly-by altitude, on reaction wheel characteristics, and on misalignments of solar arrays relative to their nominal orientation.

The mission scenario is presented in Section 2, the dust environment and fly-by characteristics are described in Section 3, attitude dynamics and control, and particle impact

models are defined in Section 4, setup of the Monte Carlo analysis is described in Section 5, along with an initial characterization of the problem and a strategy to select control gains, Section 6 then includes a more detailed analysis of the problem and recommendations for SC B1, and conclusions are finally summarized in Section 7.

2. Comet fly-by scenario and assumptions

SC B1 will separate from the main spacecraft SC A approximately two days before the fly-by (ESA, 2019), and it will be inserted into a ballistic fly-by trajectory with expected closest approach (CA), as of 2021, of 750 ± 250 km (1σ). Large fly-by speeds are expected given the typical velocities of long-period comets around the Sun (15–70 km/s, see Section 3.3). Consequently, fly-by trajectories are expected to have short durations: from ~ 20 min up to 2 h, which also allows to simplify fly-by trajectories as straight lines of constant speed: i.e., uniform, rectilinear motion relative to the comet. In fact, transfer of linear momentum through particle impacts is shown to have a negligible effect on relative fly-by speed (Section 4.2.2), and gravitational effects are expected to amount to changes in velocity of less than 1 m/s given the large distances to the comet, small nucleus sizes (less than 35 km), and average expected bulk density (570 kg/m³) considered in the dust environment model (Comet-I Dust Hazard Assessment Team, 2021; Marschall et al., 2021). As such, an instantaneously inertial reference frame I centered at the comet can also be defined (Fig. 1), which is employed throughout this study to express the relative position, velocity, and attitude of the spacecraft. The axes of reference frame I are defined as: $\hat{v}_r$, the unit vector parallel to the relative fly-by velocity, and $\hat{c}_x$ and $\hat{c}_z$, the cross-axes defining a right-handed Cartesian reference frame, with $\hat{c}_x$ parallel to the comet-spacecraft vector at the time of closest approach.

The spacecraft, of 30 kg in mass and $40\text{ cm} \times 30\text{ cm} \times 20\text{ cm}$ in size (current assumptions during conceptual design), will be equipped with a narrow-angle camera for science, MMA Design's eHawk solar arrays (MMA Design, 2021), and a bumper on the face that is

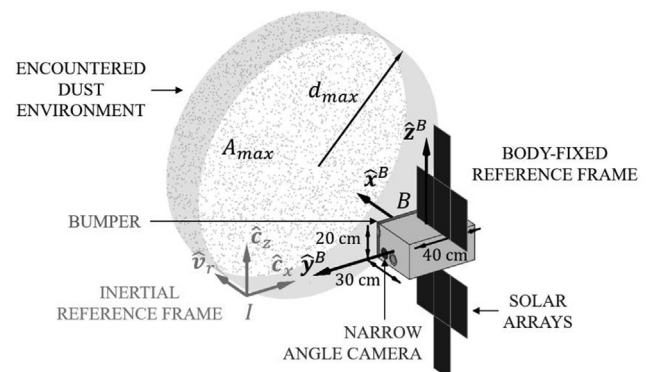


Fig. 1. Spacecraft configuration and reference frame definition.

nominally exposed to the dust environment (JAXA Comet Interceptor Team, 2021). The spacecraft is intended to maintain an inertially-fixed, three-axis stabilized orientation throughout the fly-by, which corresponds to pointing the narrow-angle camera (body-fixed axis $\hat{y}^B$) towards the comet at the time of closest approach, while keeping the bumper (body-fixed axis $\hat{x}^B$) normal to the relative fly-by velocity (see Fig. 1). Note that the maximum cross-sectional area where particle impacts may occur, containing any possible orientation of the spacecraft, is labeled as A_{max} in Fig. 1, and corresponds to a circle of radius d_{max} : distance from the center of mass of the spacecraft (CM) to the farthest corner on the solar arrays. These two variables are later employed in Section 3.2 to compute the number of particles that may be encountered along the fly-by trajectory.

The attitude is controlled by three reaction wheels aligned with each body-fixed axis: Blue Canyon Technologies' (BCT's) RWP500, with maximum torque $T_{w,lim} = 25 \text{ mN} \cdot \text{m}$ and maximum angular momentum $H_{w,lim} = 500 \text{ mN} \cdot \text{m} \cdot \text{s}$ (Blue Canyon Technologies, 2021). Attitude knowledge is provided by a star tracker and three gyroscopes aligned with body-fixed axes (JAXA Comet Interceptor Team, 2021), and attitude requirements for the science phase have been established as $\varepsilon_{req} \leq 0.5^\circ$ in pointing error, and $\omega_{req} \leq 0.4 \text{ deg/s}$ in angular velocity, which should be accomplished despite dust particle impacts and component inaccuracies (modeled in Section 4.2).

In lack of a more detailed model of internal mass distribution, the main body of the spacecraft is assumed to be homogeneous with inertia tensor $\underline{J}_{24U}$ (excluding reaction wheels), and solar arrays are modeled as thin plates with inertia tensor $\underline{J}_{SA}$, nominally oriented parallel to the incoming flow of particles (as shown in Fig. 1). Note that it is further assumed here that the spacecraft's main body and the solar arrays behave as a rigid body: i.e., they rotate with the same angular velocity. Additionally, the validity of modeling solar arrays as plates with zero thickness and the effects of solar array orientation are discussed in Section 6.3. The total moment of inertia of the spacecraft (including reactions wheels and solar arrays) can therefore be described as $\underline{J}_T = \underline{J}_{SC} + {}^w\underline{A}^B \underline{J}_w {}^w\underline{A}^{BT}$ if all inertia tensors are expressed relative to CM, where $\underline{J}_{SC} = \underline{J}_{24U} + {}^{SA}\underline{A}^B \underline{J}_{SA} {}^{SA}\underline{A}^{BT}$ is the moment of inertia of the main body plus solar arrays, $\underline{J}_w = \text{diag}([J_{w1}, J_{w2}, J_{w3}])$ is the axial moment of inertia of reaction wheels, ${}^{SA}\underline{A}^B$ projects solar array principal axes onto body-fixed reference frame B , and ${}^w\underline{A}^B$ projects the spin axis of reaction wheels onto frame B .

3. Dust environment

The number of dust particles encountered by SC B1 along its fly-by trajectory will depend on factors such as

the actual fly-by altitude, cometary dust production rate, or the surface area exposed to the dust environment. Fly-by altitude and comet-related characteristics represent the main sources of uncertainty for the mission. In an effort to constrain and describe the potential dust environments to be encountered by SC A, SC B1 and SC B2, Comet-I's Dust Hazard Assessment Team developed an Engineering Dust Coma Model (EDCM) that estimates the number and size of particles along the trajectory of each spacecraft (Comet-I Dust Hazard Assessment Team, 2021; Marschall et al., 2021): for baseline fly-by altitudes of 200 km (SC B2), 500 km (SC B1), and 1000 km (SC A). A brief overview of the EDCM is provided in Section 3.1, and it is then adapted for use in the Monte Carlo analysis in Section 3.2.

3.1. Engineering dust Coma model

The EDCM takes a series of stochastic variables as inputs: e.g., comet nucleus radius, bulk density, gas production rate, dust-to-gas mass production rate, or dust size distribution (Marschall et al., 2021; Zakharov et al., 2021a, 2021b). Based on these inputs, the EDCM models the dynamics of dust particles around the comet to simulate their motion and describe the distribution of the cometary dust environment, taking into consideration effects such as gas drag force, gravity attraction of the nucleus, and solar radiation pressure. Through a Monte Carlo analysis, the EDCM is then able to describe the range of possible dust environment scenarios to be encountered by the spacecraft, and provides these results in the form of number of particles per m^3 (i.e., spatial density of particles) along fly-by trajectories.

The EDCM expresses the spatial density of particles n as a vector of length N at discrete distances d_k from the comet: for $k \in [0, N - 1]$. Such density of particles depends on the particle size, and so n is provided for various particle radii: for particles of size $[1 \cdot 10^{-6}, 3.16 \cdot 10^{-6}] \text{ m}$, $[3.16 \cdot 10^{-6}, 1 \cdot 10^{-5}] \text{ m}$, $[1 \cdot 10^{-5}, 3.16 \cdot 10^{-5}] \text{ m}$, etc. (grouped in half-decade intervals). Further, since the spatial density of particles is a stochastic variable, n is statistically summarized in the form of percentiles, which effectively represent the probability of encountering a given number of particles at a certain distance from the comet. Table 1 provides an example of how the outputs of EDCM are expressed, and these are then illustrated in Fig. 2, where negative/positive values of distance to comet indicate pre/post closest approach. Take, for instance, the central column in Table 1 as an example (50th percentile): in the best 50% percent of the cases, at distance $d_0 = 50,000 \text{ km}$ from the comet (farthest data point provided by the EDCM), the expected number of particles of size $1 \cdot 10^{-6} - 3.16 \cdot 10^{-6} \text{ m}$ is of up to 0.0021 per m^3 , and, at 1000 km from the comet (at CA), the expected number of particles of this size is of up to 21.975 per m^3 .

Several observations on the expected number and size of particles to be encountered can already be made from the EDCM outputs, for instance: (a) smaller particles are more

numerous than larger particles, (b) environment density increases closer to the comet, and (c) the uncertainty in number of particles is of several orders of magnitude, and this uncertainty is larger for larger particles. Several of these observations can be further leveraged to adapt the results of the EDCM for a Monte Carlo analysis in which the dust environment (the number and size of particles, and their spatial distribution) is randomized.

3.2. Adapting the EDCM for Monte Carlo analysis

It is first noticed that EDCM provides number of particles for various particle sizes (grouped in half-decade intervals of particle radius) with an average expected density of 570 kg/m^3 . Note also that the linear momentum of impacted particles—which is relevant to attitude perturbations—is linearly proportional to their mass. Such a discretization of particle radius thus results in a coarse discretization of particle mass, and, consequently, of transferred linear and angular momenta: every 1.5 decades. A finer discretization of particle mass is desirable for the Monte Carlo analysis, so as to more realistically represent a continuum of particles, and this can be achieved by observing the linear relationship (in a log–log scale) between number of particles and particle size (see Fig. 3).

It is therefore possible to refine the discretization of particle size (or mass) provided by EDCM while preserving the observed relationship in Fig. 3. In this study, the coarser discretization provided by EDCM (every half decade) is refined by a factor of 10, which then results in a discretization of particle mass (and of transferred momenta) every ~ 1.5 tenths of a decade (instead of every 1.5 decades). As an example for reference, Fig. 3 specifically illustrates 50th-percentile values at the closest approach of a 1000-km fly-by, and it may be read as follows: illustrated as tall, wide columns are the values provided by EDCM, which follow a linear trend and represent the expected number of particles corresponding to various size intervals. EDCM values indicate, for instance, that up to $10^0 = 1$ particle per m^3 is expected in the size range $[3.16 \cdot 10^{-6}, 1 \cdot 10^{-5}] \text{ m}$ (second wide column from the left). Illustrated as narrower, shorter columns is then the refined discretization of particle size employed in this study, which follows the same linear trend as the EDCM values and expresses the expected number of particles for smaller intervals of particle size. Note, lastly, that this finer discretization is computed in such a way that the cumulative number of particles corresponding to a given size interval (e.g., sum of narrow columns between $3.16 \cdot 10^{-6}$ and $1 \cdot 10^{-5} \text{ m}$) is equal to the number of particles indicated by the EDCM

Table 1

Number of particles of radius $1 \cdot 10^{-6}$ – $3.16 \cdot 10^{-6} \text{ m}$ per m^3 along 1000-km fly-by (summarized from (Marschall et al., 2021)).

Distance to comet	Number of particles per m^3 (percentile)								
	1st	5th	10th	25th	50th	75th	90th	95th	99th
50,000 km	0.0003	0.0004	0.0006	0.0011	0.0021	0.0033	0.0043	0.0048	0.0057
40,000 km	0.0004	0.0007	0.0009	0.0017	0.0033	0.0051	0.0067	0.0076	0.0090
30,000 km	0.0008	0.0012	0.0016	0.0031	0.0060	0.0093	0.0122	0.0138	0.0164
20,000 km	0.0018	0.0028	0.0037	0.0072	0.0139	0.0217	0.0282	0.0319	0.0381
10,000 km	0.0077	0.0121	0.0161	0.0315	0.0609	0.0949	0.1245	0.1416	0.1806
5000 km	0.0352	0.0552	0.0728	0.1427	0.2747	0.4285	0.5569	0.6287	0.7506
1000 km	2.7479	4.2560	5.8471	11.472	21.975	34.491	46.221	54.973	72.552

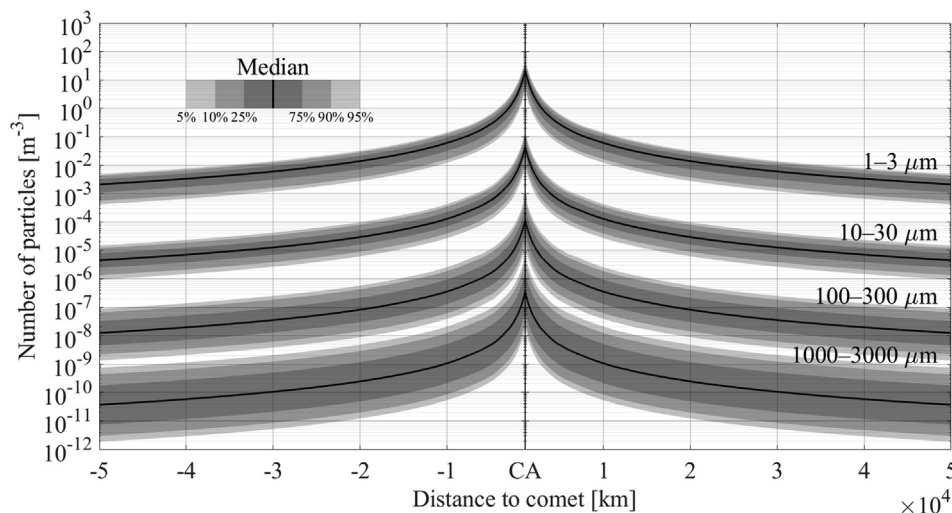


Fig. 2. Number of dust particles per m^3 along 1000-km fly-by, for various particle sizes (reproduced from (Marschall et al., 2021)).

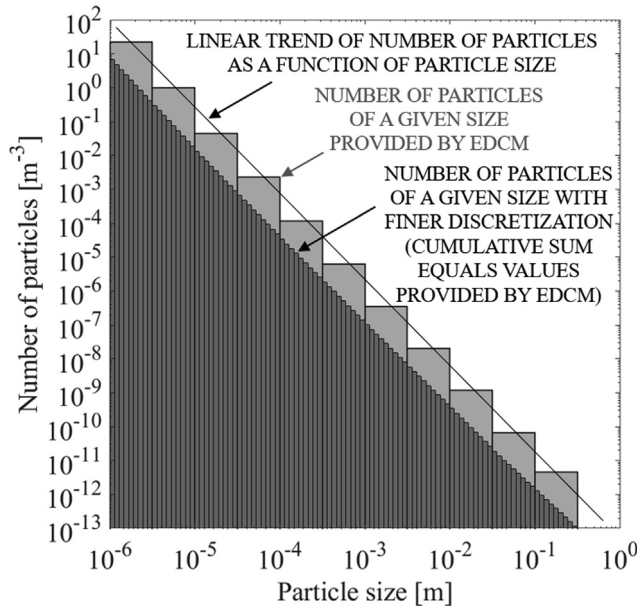


Fig. 3. Relationship between number of particles and particle size, 50th percentile at closest approach for 1000-km fly-by (modified from (Marschall et al., 2021)).

columns (i.e., $10^0 = 1$ particle per m^3 in this specific example).

Similarly, it is noticed that EDCM represents the stochasticity of the dust environment in the form of density percentiles (those shown in Table 1): 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th. Again, a finer discretization of these percentiles is desirable for the Monte Carlo analysis, so as to be able to consider intermediate values to these percentiles when randomizing the density of the dust environment. After plotting the number of particles against the provided percentiles in a log-linear scale (Fig. 4), it is decided to linearly interpolate, in this scale, dust environment densities in between the percentiles provided by the EDCM. This approach is also seen to be valid throughout the fly-by trajectory, since the behavior of number of particles *versus* density percentiles is similar regardless of distance to comet (Fig. 4).

Once a finer discretization in terms of particle size/mass and dust environment densities is available, it is further noticed that EDCM results are provided only for the baseline fly-by altitudes of SC B2, SC B1, and SC A: 200 km, 500 km, and 1000 km, respectively. Since the fly-by altitude of SC B1 is, in fact, uncertain, it is also desirable to approximate the dust environment for intermediate fly-by altitudes within the 200–1000 km range, and for altitudes outside of this range. Several observations can be made when plotting the number of particles against the distance to the comet for the three baseline fly-by altitudes (solid black lines in see Fig. 5, in a log–log scale).

It is firstly observed that, at far distances from the comet, the number of particles per m^3 for the three baseline fly-by altitudes converge and tend to zero (right-most points of the three solid lines in Fig. 5, at

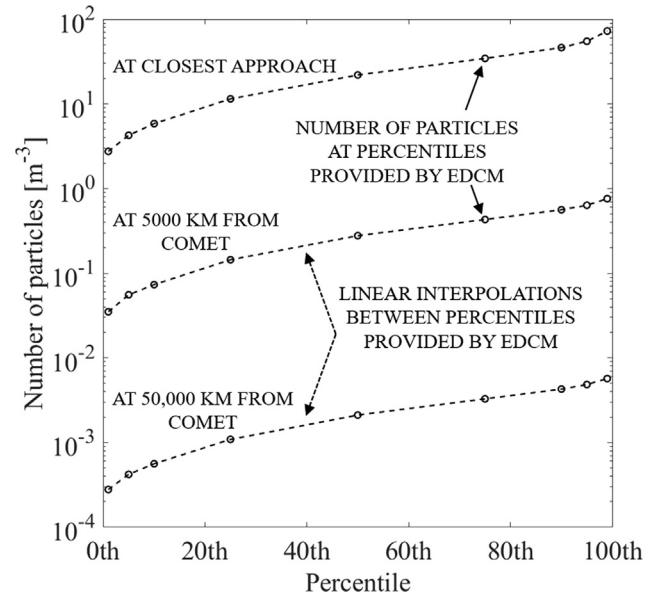


Fig. 4. Relationship between number of particles and dust environment density, for 1000-km fly-by and particles $1 \cdot 10^{-6}$ – $3.16 \cdot 10^{-6}$ m in size (modified from (Marschall et al., 2021)).

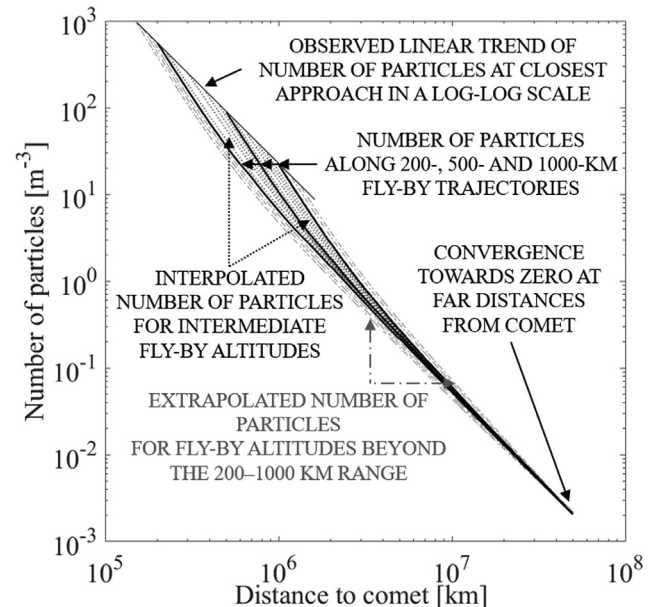


Fig. 5. Relationship between number of particles and distance to comet, 50th percentile for particles $1 \cdot 10^{-6}$ – $3.16 \cdot 10^{-6}$ m in size (modified from (Marschall et al., 2021)).

$d_0 = 50,000$ km). It is also observed that the maximum number of particles occurs at closest approach, and a linear trend can be observed between the maximum number of particles for the baseline fly-by altitudes (left-most points of the three solid lines in Fig. 5, at CA). It is lastly observed that, for each fly-by altitude, the number of particles against distance to comet follows a non-linear trend in this log–log scale, and a polynomial fit can be used to approximate its behavior (although alternative approaches may be

suitable too). In this study, it is determined that a sixth-degree polynomial can faithfully represent the trend of spatial density of particles n against distance to comet d for each of the baseline fly-by altitudes, in the form of: $\log(n) \approx \sum_i a_i \log(d)^i$ for $i \in [0, 6]$.

It is further seen that dust environments in between the baseline fly-by altitudes can be approximated by linear interpolation of polynomial coefficients a_i for $i \in [1, 5]$, and solving for the leading coefficient a_6 and the constant of the polynomial a_0 in a linear system of two equations. A first equation may capture the tendency towards zero at far distances from the comet (at d_0), and the second equation can capture the linear trend of maximum number of particles at closest approach (at d_{CA}), such as shown in Eq. (1). The resulting dust environments for intermediate fly-by altitudes are represented by dashed lines in Fig. 5.

$$\begin{bmatrix} \log(n)|_{at\ d_{CA}} \\ \log(n)|_{at\ d_0} \end{bmatrix} = \begin{bmatrix} 1 & \log(d_{CA})^6 \\ 1 & \log(d_0)^6 \end{bmatrix} \begin{bmatrix} a_6 \\ a_0 \end{bmatrix} + \begin{bmatrix} \sum_i a_i \log(d_{CA})^i \\ \sum_i a_i \log(d_0)^i \end{bmatrix} \text{ for } i \in [1, 5] \quad (1)$$

For fly-by altitudes beyond the 200–1000 km range, it is seen that fixing the polynomial coefficients a_i for $i \in [1, 5]$ equal to those at 200 km or 1000 km (for altitudes below 200 km and above 1000 km, respectively) and modifying only a_6 and a_0 can preserve the overall behavior of number of particles as a function of distance to comet, although no statement can be made on the physical validity of these extrapolations. The resulting dust environments outside the 200–1000 km range are represented by dash-dotted lines in Fig. 5.

In summary, EDCM results (provided as in Table 1 and Fig. 2) are adapted for the Monte Carlo analysis through: (1) a refinement of the particle size/mass discretization, (2) a refinement of the percentile discretization, and (3) an interpolation/extrapolation of the dust environment for different fly-by altitudes. Recall, lastly, that the spatial density of particles n is provided at discrete distances d_k from the comet: for $k \in [0, N - 1]$ (such as in Table 1). In order to compute the number of particles within the volume spanned by the trajectory between points d_k and d_{k+1} , a simple trapezoidal rule is employed to integrate n in the $[d_k, d_{k+1}]$ interval, and this integral is then multiplied by the maximum cross-sectional area of the spacecraft A_{max} where potential impacts may occur (Fig. 1). In the Monte Carlo analysis, these particles are then distributed along the $[d_k, d_{k+1}]$ interval and over the area A_{max} according to uniform random distributions. Whether or not one of these particles will actually collide with the spacecraft will depend on the orientation of the spacecraft at the time of encounter, and the process of determining whether a given particle impacts or not the spacecraft is described in Section 4.2.1. As a note, cloud-like regions with a higher density of particles, or *vice versa*, such as those observed by the Rosetta spacecraft (Grün et al., 2016), are not considered

in this analysis, and the assumed uniform spatial distribution of particles can be taken as the averaged effect of higher and lower density regions along the fly-by.

3.3. Impact velocity

Besides a highly-active and uncertain dust environment, the design phases of Comet-I are also challenged by a large and *a priori* uncertain relative velocity between the spacecraft and the target comet at the time of fly-by. This uncertainty in relative fly-by speed then directly translates into an uncertainty in dust particle impact speeds. The range and distribution of potential relative fly-by speeds employed in this study are obtained from Sánchez et al. (2021), which analyzed the intercept transfer trajectories to a population of 1700 synthetic long-period comets with perihelia below 2 au (emulating potential targets). The population of synthetic long-period comets was generated by Boe et al. (2019), based on best current knowledge of Oort-cloud comet orbital distribution. Sánchez et al. then showed that, out of the 1700 synthetic objects, 306 comets were potentially reachable within the bounds of spacecraft constraints and mission requirements (e.g., propulsive capability, transfer time, maximum relative velocity of 70 km/s, fly-by solar aspect angle between 45 and 135 deg, etc.).

Illustrated in Fig. 6 is then the distribution of these 306 comets as a function of relative fly-by speed, which highlights the large uncertainty in relative fly-by speed for the Comet-I mission. Relative fly-by speeds (and, thus, particle impact speeds) can easily range from 15 up to 70 km/s. In the Monte Carlo analysis performed in this study, the relative fly-by speed is randomized for each Monte Carlo case according to the probability distribution shown in Fig. 6. It is further noted by Sánchez et al. that such large range of possible fly-by speeds is primarily a result of the geometry of the encounters, being the inclination of the long-period comets along their heliocentric trajectories the main variability factor.

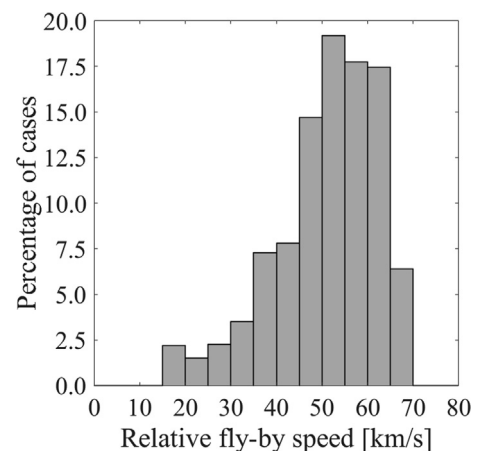


Fig. 6. Distribution of relative fly-by speeds of reachable long-period comets.

4. Attitude dynamics and control

Once the dust environment and fly-by characteristics are modeled and randomized for the Monte Carlo analysis, the modeling of attitude dynamics and control, including component inaccuracies, and the identification and effect of particle impacts are described in this section.

4.1. Dynamics and control

Following the nomenclature in Kumar et al. (2018), the attitude dynamics of a spacecraft controlled by reaction wheels can be described as in Eq. (2).

$$\underline{J}_{SC}\dot{\omega}^B = -\omega^B \times (\underline{J}_T \omega^B + {}^w \underline{A}^B \underline{J}_w \Omega_w) + \underline{T}_w^B + \underline{T}_E^B \quad (2)$$

where superscript B denotes variables expressed in the body-fixed frame B , ω is the angular velocity of the spacecraft (i.e., main body plus solar arrays) relative to an inertial reference frame, $\Omega_w = [\Omega_{w,x}, \Omega_{w,y}, \Omega_{w,z}]^T$ is the axial angular velocity of three reaction wheels, assumed to be perfectly aligned with body-fixed axes: i.e., ${}^w \underline{A}^B = \underline{I}_{3 \times 3} \equiv$ identity matrix, $\underline{T}_w$ is the torque generated by reaction wheels, and $\underline{T}_E$ is the external torque acting on the system (although no external torque is considered in this study: $\underline{T}_E = 0$). Note that the perturbations generated by impacts of dust particles are introduced in this analysis as instantaneous changes in angular velocity (see Section 4.2.2), and not as an external torque. Lastly, the torque generated by reaction wheels $\underline{T}_w$ is a combination of the torque commanded by the on-board computer $\underline{T}_{w,c}$ and the perturbing torques $\underline{T}_{w,p}$ due to static and dynamic imbalance of reaction wheels (see Section 4.2): $\underline{T}_w = \underline{T}_{w,c} + \underline{T}_{w,p}$.

In this study, the on-board computer is assumed to compute a desired, commanded torque generated by reaction wheels (based on pointing error and angular velocity), which then determines the required angular acceleration of reaction wheels $\dot{\Omega}_w$. A relationship between the generated torque and the angular acceleration of reaction wheels and of the spacecraft can be obtained from the derivative in axial angular momentum of reaction wheels $\dot{H}_w = [\dot{H}_{w,x}, \dot{H}_{w,y}, \dot{H}_{w,z}]$ (see Eq. (3)).

$$\underline{T}_w = -\dot{H}_w = -\underline{J}_w \left(\dot{\Omega}_w + {}^w \underline{A}^{BT} \omega^B \right) \quad (3)$$

where the negative sign underlines the action-reaction effect of wheels on the spacecraft. Notice that $\dot{\Omega}_w$ is computed through Eq. (3) based on the quantities that are known by the on-board computer: i.e., substituting $\underline{T}_w$ by $\underline{T}_{w,c}$, and computing $\dot{\omega}$ (Eq. (2)) based on $\underline{T}_{w,c}$ and on the on-board knowledge of ω . Further, reaction wheel angular velocity and moments of inertia are assumed to be perfectly known. Lastly, note that the saturation limit of reaction wheels is also considered: $H_w \leq H_{w,lim}$, but, as shown in Section 6.1, saturation is not reached unless reaction wheels are heavily loaded prior to the fly-by.

The goal of the attitude controller is to mitigate the perturbation of particle impacts and to stabilize the spacecraft about a desired, inertially-fixed orientation (i.e., zero angular velocity ω). A simple quaternion-feedback control logic (Wie, 2016) is employed here since the focus of the study is to understand and characterize the highly uncertain attitude performance of the spacecraft rather than providing the most efficient or robust control logic. This simple feedback controller thus allows to preliminarily assess the feasibility of the mission, to identify main mission and environment factors, and to evaluate the effect of reaction wheel capability and of solar array configuration.

Following the nomenclature in (Wie, 2016), consider a desired orientation $\underline{q}_c = [q_{c1}, q_{c2}, q_{c3}, q_{c4}]^T$ represented in quaternion form (relative to an inertial reference system). Assuming the spacecraft attitude $\underline{q}_{SC} = [q_1, q_2, q_3, q_4]^T$ is known through star tracker observations (including errors), and the angular velocity ω is known through gyroscope measurements (including errors), the attitude error $\underline{q}_e = [q_{e1}, q_{e2}, q_{e3}, q_{e4}]^T = [\underline{q}_e^T, q_{e4}]^T$ with respect to the desired orientation can be computed on board as in Eq. (4). The quaternion $\underline{q}_e = \cos(\varepsilon/2) + \sin(\varepsilon/2)\hat{\mathbf{e}}$ effectively describes the shortest rotation between $\underline{q}_c$ and $\underline{q}_{SC}$: a rotation of angle ε (pointing error) about axis $\hat{\mathbf{e}}$. The torque required from reaction wheels can then be defined as in Eq. (5) (in the body-fixed reference frame). Also note that, if the required torque from any one reaction wheel (Eq. (5)) exceeds the maximum allowable torque $T_{w,lim}$, the magnitude of the commanded torque (i.e., in vector $\underline{T}_{w,c}$) for that particular wheel is set equal to $T_{w,lim}$.

$$\begin{bmatrix} q_{e1} \\ q_{e2} \\ q_{e3} \\ q_{e4} \end{bmatrix} = \begin{bmatrix} q_{c4} & q_{c3} & -q_{c2} & -q_{c1} \\ -q_{c3} & q_{c4} & q_{c1} & -q_{c2} \\ q_{c2} & -q_{c1} & q_{c4} & -q_{c3} \\ q_{c1} & q_{c2} & q_{c3} & q_{c4} \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \end{bmatrix} \quad (4)$$

$$\underline{T}_w^B = -\underline{K}\underline{q}_e - \underline{C}\omega^B \quad (5)$$

where $\underline{K}$ and $\underline{C}$ are the proportional and derivative gains of the controller.

Several gain selections can achieve global asymptotic stability (Wie, 2016), and the definition in Eq. (6) is adopted in this study.

$$\underline{K} = \text{sgn}(q_{e4}) \cdot k \cdot \underline{I}_{3 \times 3} \text{ for } \underline{C} = c \cdot \underline{I}_{3 \times 3} \quad (6)$$

where $\text{sgn}(\cdot)$ is the signum function and selects the shorter angular path towards the desired orientation, and k and c are two positive scalar constants. The gain selection process is described in Section 5.2.

4.2. Errors and perturbances

Errors considered in this study are associated to on-board sensors and actuators: star tracker (attitude knowledge), gyroscopes (angular velocity knowledge), and reaction wheels (generated torque). Star tracker accuracy (1σ) is described in its specifications as: 6 arcsec in cross-

boresight and 40 arcsec in boresight direction (Hegel, 2016; JAXA Comet Interceptor Team, 2021), but this baseline performance may be jeopardized by cometary dust particles within the field of view: as experienced by ESA's Rosetta spacecraft during its 15-km fly-by of short-period comet 67P/Churyumov-Gerasimenko (Pérez-Ayúcar et al., 2018; Vallat et al., 2017). At closest approach, even along a baseline 750-km fly-by, SC B1 is expected to encounter two and up to eight orders of magnitude denser dust environments than that experienced by Rosetta (Merouane et al., 2016), depending on the characteristics of the target long-period comet. Development of a robust attitude determination system under such extreme conditions is thus essential for the success of the mission and remains a topic for future work. As suggested for close-proximity operations around comets (Lisse et al., 2022), such a system may rely on a star tracker with a more robust software for detection of real stars and rejection of dust particles within the field of view, or on integrated gyroscope measurements that may still provide sensible accuracies given the short duration of the close encounter. In lack of a more informed estimation on attitude determination performance, however, this analysis assumes the baseline star tracker performance considered in the SC B1 Design Report Document (JAXA Comet Interceptor Team, 2021), and the effect of larger attitude knowledge inaccuracies is commented in Section 6.1.

Error in attitude knowledge is then introduced in the Monte Carlo simulations as two consecutive rotations about the true orientation of the spacecraft (frame B in Fig. 7): a first rotation α_1 (with zero mean and baseline standard deviation $\sigma_1 = 6$ arcsec) about a uniformly-random cross-boresight direction $\hat{\lambda}_1$ (which results in intermediate frame B_1), and a second rotation α_2 (with zero mean and baseline standard deviation $\sigma_2 = 40$ arcsec) about the boresight direction of frame B_1 : $\hat{y}_1$ (the $\hat{y}$ -axis in Fig. 7 corresponds to the true boresight direction of the spacecraft). This pointing error is time varying and randomized for each Monte Carlo simulation.

Angular velocity ω^B is assumed to be known through three gyroscopes aligned with body-fixed axes. A constant bias in angular velocity is introduced along each of these axes: zero mean and standard deviation of 10 deg/h, according to typical bias stabilities of small-spacecraft gyroscopes (NASA, 2020). Such constant biases are randomized and introduced in each Monte Carlo simulation.

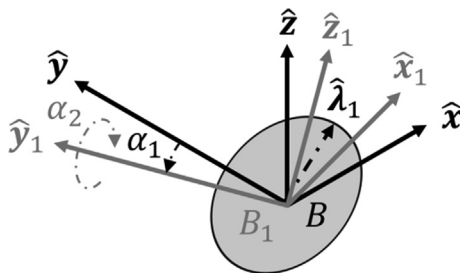


Fig. 7. Modeling of star tracker boresight and cross-boresight accuracy.

Lastly, reaction wheel inaccuracies, due to asymmetries in radial and axial mass distribution, are typically modeled as static and dynamic imbalance. Reported static and dynamic imbalances for BCT reaction wheels are: $S \leq 3 \text{ g} \cdot \text{mm}$ and $D \leq 25 \text{ g} \cdot \text{mm}^2$, respectively (Blue Canyon Technologies, 2021). Notice that the generated perturbation due to static imbalance is expected to be approximately two orders of magnitude smaller than that due to dynamic imbalance, since the static imbalance is proportional to S , to the spin velocity of the wheels squared: $\Omega_{w,x}^2$, $\Omega_{w,y}^2$ and $\Omega_{w,z}^2$, and to the distance from the wheel to the center of mass of the spacecraft (in the order of tens of centimeters for a 24U-sized spacecraft). The perturbing torque due to dynamic imbalance, on the other hand, is only proportional to D ($\gg S$) and to the spin velocity of the reaction wheels squared: and not to the distance from the wheel to the center of mass. Only the dynamic imbalance is thus considered in this study when computing the perturbing torque $T_{w,p}$ (see Eq. (7)).

$$\begin{aligned} T_{w,p} = & \left(D_z \Omega_{w,z}^2 \sin(\Omega_{w,z} t + \phi_z) - D_y \Omega_{w,y}^2 \cos(\Omega_{w,y} t + \phi_y) \right) \hat{x}^B \\ & + \left(D_x \Omega_{w,x}^2 \sin(\Omega_{w,x} t + \phi_x) - D_z \Omega_{w,z}^2 \cos(\Omega_{w,z} t + \phi_z) \right) \hat{y}^B \\ & + \left(D_y \Omega_{w,y}^2 \sin(\Omega_{w,y} t + \phi_y) - D_x \Omega_{w,x}^2 \cos(\Omega_{w,x} t + \phi_x) \right) \hat{z}^B \end{aligned} \quad (7)$$

where D_x , D_y , and D_z are the dynamic imbalances of reaction wheels aligned with body-fixed $\hat{x}^B$, $\hat{y}^B$ and $\hat{z}^B$ axes, respectively, t is the time variable, and ϕ_x , ϕ_y , and ϕ_z are arbitrary initial phases associated to each reaction wheel. In each Monte Carlo simulation, dynamic imbalances D_x , D_y , and D_z are uniformly randomized in the $[0, 25] \text{ g} \cdot \text{mm}^2$ range, and initial phases ϕ_x , ϕ_y , and ϕ_z are uniformly randomized in the $[0, 2\pi]$ rad range.

4.3. Identification of particle impacts

The predominant source of perturbations for the Comet-I mission, however, are dust particle impacts. Randomized dust environments are generated in each Monte Carlo simulation as described in Section 3. Each particle in the dust environment is then described by a mass m_p , and a position $\mathbf{r}_p = x_p \hat{\mathbf{e}}_x + y_p \hat{\mathbf{e}}_y + z_p \hat{\mathbf{e}}_z$ in inertial reference frame I (centered at the comet). Notice that, in such reference frame, the position of the spacecraft along its fly-by trajectory can simply be described as $\mathbf{r}_{SC} = h_f \hat{\mathbf{e}}_x + (y_0 + v_r t) \cdot \hat{\mathbf{v}}_r$, where h_f is the fly-by altitude, y_0 is the initial position of the spacecraft along the $\hat{\mathbf{v}}_r$ -axis, and v_r is the relative fly-by speed. Regardless of the orientation of the spacecraft, potential particle impacts are then assumed to occur at time t_p : when $y_0 + v_r t_p = y_p \iff t_p = (y_p - y_0)/v_r$ (i.e., when the $\hat{\mathbf{v}}_r$ -coordinate of the spacecraft's CM coincides with that of the particle).

At the time t_p of each potential impact, the orientation of the spacecraft and the cross-axis coordinates x_p and z_p

of the particle are examined to determine whether an impact actually occurs, and on which face of the spacecraft (Fig. 8). Initially, the following two steps are verified:

- 1) For each face f of the spacecraft, with outward normal $\hat{n}_f$, check if $\hat{n}_f \cdot \hat{v}_r > 0$: i.e., if face f is oriented towards the incoming flow of particles.
- 2) If so, project the vertices of face f onto the $\hat{c}_x$ - $\hat{c}_z$ plane, and check if point (x_p, z_p) is contained within the polygon described by the projected vertices. The methodology in (Hormann and Agathos, 2001) is implemented to solve this “point-in-polygon” problem.

If 1) and 2) are fulfilled, then an impact between the particle and face f will occur, unless another face f' is impacted by the particle before: this may happen if particles impact solar arrays before the main body of the spacecraft, or *vice versa*. If point (x_p, z_p) is contained within the polygons described by the projected vertices of both faces f and f' , it then has two potential points of impact: (x_p, y_f, z_p) and $(x_p, y_{f'}, z_p)$, and one must check which face is impacted first (i.e., which potential point of impact is farther upstream): $y_f > y_{f'}$ or $y_f < y_{f'}$. In the example in Fig. 8, the scenario is presented where no impacts occur on the closest region on the solar arrays to the main body of the spacecraft, since the bumper is farther upstream and thus firstly exposed to the dust environment.

In order to determine the coordinate y_f (or $y_{f'}$) of the potential point of impact with face f (or f'), the definition of the plane to whom face f belongs can be leveraged. Note that, if the normal of face f is $\hat{n}_f = n_{f,x}\hat{c}_x + n_{f,y}\hat{v}_r + n_{f,z}\hat{c}_z$ and one of its vertices is at $p_x\hat{c}_x + p_y\hat{v}_r + p_z\hat{c}_z$, the equation of the plane yields Eq. (8).

$$n_{f,x}(x_p - p_x) + n_{f,y}(y_f - p_y) + n_{f,z}(z_p - p_z) = 0 \quad (8)$$

from which the $\hat{v}_r$ -component y_f of the potential point of impact can be computed. If such an operation is performed

for faces f and f' , then, by comparing y_f and $y_{f'}$, one may determine which potential point of impact is farther upstream. Notice that, in this study, a given particle is assumed to only impact one face (i.e., the first one to be impacted), and no downrange or back-scattered ejecta impacting on other faces is modeled (i.e., no secondary impacts).

4.4. Attitude perturbation due to particle impacts

Through Section 4.2.1 it is thus possible to determine whether an impact with a particle at time t_p will occur, and on which face of the spacecraft. The impact point of the particle (of mass m_p) is then described relative to CM as $\mathbf{r}_p^{CM} = (x_p - h_f)\hat{c}_x + (y_f - y_p)\hat{v}_r + z_p\hat{c}_z$, and the velocity of the particle relative to the spacecraft is $\mathbf{v}_p = -v_r\hat{v}_r$ (i.e., anti-parallel to the relative fly-by velocity). Particle impacts are assumed to produce instantaneous changes in spacecraft angular momentum (or angular velocity) as a function of particle mass, velocity, impact point and incidence angle, and impacted material.

Impacts exceeding the speed of sound on solid materials are categorized as “hypervelocity” impacts, which generally result in the perforation/cratering of the impacted face, and generation of downrange (downstream) and back-scattered (upstream) ejecta (Rival and Mandeville, 1999). Such ejecta then generates a momentum transfer that is larger than the linear momentum of the incoming particle: this is known as “momentum enhancement” (i.e., the ratio of transferred momentum over the linear momentum of the incoming particle is larger than one). As a countermeasure, SC B1 will feature a bumper on the face that is nominally exposed to the dust environment (Fig. 1), with the purpose of plastically absorbing the linear momentum of incoming particles (i.e., ratio equal to one). As an initial step in the analysis, all impacts are modeled as perfectly plastic regardless of the impacted surface (results in all of Section 6 unless otherwise specified), and, subsequently, impacts on faces other than the bumper are modeled as hypervelocity impacts as a case study (results in Section 6.2): to assess

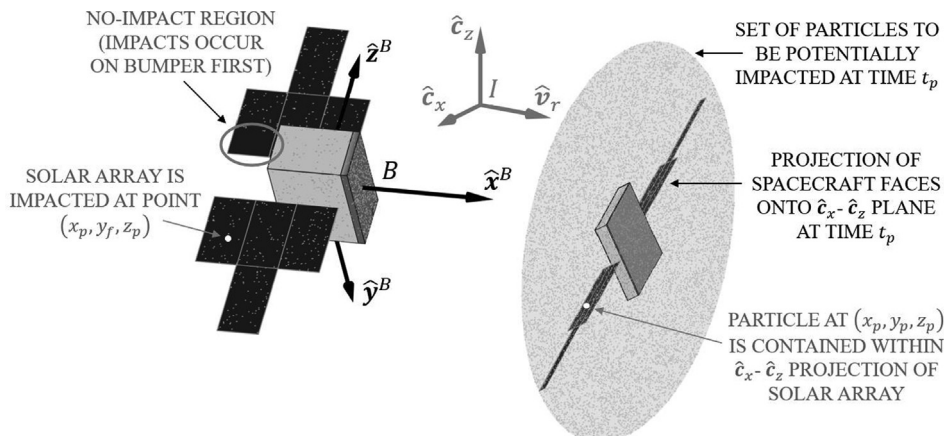


Fig. 8. Example of set of particles to be potentially impacted by spacecraft and identification of impact points.

the effect of momentum enhancement. Notice also that, when modeling hypervelocity impacts, only back-scattered ejecta is considered (which enhances momentum transfer), and no downrange ejecta is modeled: which is generally generated on thin materials and may damage internal components, but results in a reduced momentum transfer.

Hypervelocity impacts have been extensively studied through empirical and theoretical data (IADC WG3, 2013), and three main types of fragments are identified to be generated: jet, cone, and spall fragments. Mathematical models for the amount of mass and velocity distribution (i.e., linear momentum) of these three types of fragments are described by (Rival and Mandeville, 1999) and employed here. Notice, however, that jetting is expected to account for less than 1% of the total ejected mass, and so jettisoned fragments are neglected in this study. Such models are expressed as a function of the kinetic energy of the impact particle, impact incidence angle, and impacted material, and they have also been employed by ESA's software MASTER-2009 to provide a reference model of the near-Earth particulate environment (Institute of Space Systems, 2020). The same combination of input parameters from (Rival and Mandeville, 1999) and (Institute of Space Systems, 2020) employed by (Sagnières and Sharf, 2017) is used here, except for the density of the impactors (i.e., dust particles), which is set equal to the average expected bulk density of the target comet: 570 kg/m^3 (Comet-I Dust Hazard Assessment Team, 2021; Marschall et al., 2021). Such model is argued to be valid for impacts with brittle materials, impactor radii between $2.5 \text{ }\mu\text{m}$ and 0.5 mm , and impact velocities between 1 km/s and 20 km/s (Institute of Space Systems, 2020).

Notice that the expected impact velocities for Comet-I (i.e., between 15 and 70 km/s , see Fig. 6) lie beyond the validity range of the employed impact model. The model, in fact, overestimates the momentum enhancement produced by hypervelocity impacts above 25 km/s by a factor of up to 2–3 when compared to experimental data and measurements (Fig. 9). Fig. 9 illustrates the momentum enhancement estimated by the employed model together with that estimated by models developed by Rembor (Rembor, 1993) and Nysmith-Denardo (Nysmith and Denardo, 1969) based on experimental data and measurements from the mission Giotto (McDonnell, 2002; McDonnell et al., 1986). It is observed how the employed model conforms to the experimental data and measurements in the 1 – 25 km/s range, but it overestimates momentum enhancements beyond this range. As such, results in Section 6.2 can be treated as a conservative estimation of the expected attitude performance of SC B1 in the presence of momentum enhancement due to hypervelocity impacts.

Similarly, as shown in Section 5.3, particles of mass larger than 10^{-8} kg (i.e., 0.2-mm radius) are expected to have a significant effect on attitude performance, and particles of up to 10^{-1} kg (i.e., 3.5-cm radius) may still be encountered, although they are more unlikely. As such, considered par-

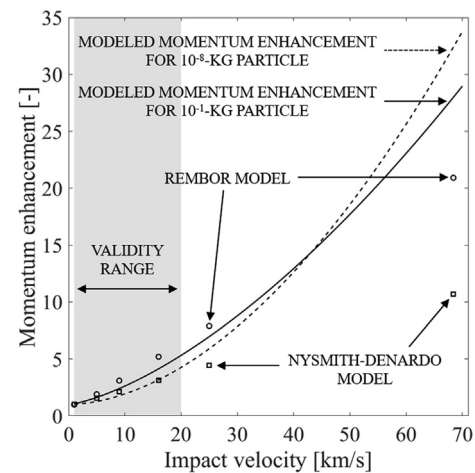


Fig. 9. Momentum enhancement due to hypervelocity impacts as a function of impact velocity.

ticle sizes (i.e., from 0.2 mm to 3.5 cm) partially lie beyond the validity range of the employed impact model too. The validity of the employed model outside of this range may only be speculated, but Fig. 10 is provided to show the behavior of the modeled momentum enhancement as a function of impactor radius.

It is observed how the locally linear and descending trend of the momentum enhancement within the validity range experiences a change in slope for particles above a 0.5-mm radius. This change in trends is more prominent for large impact velocities. Despite the uncertainty of whether the modeling for radii above 0.5 mm is or not physically representative, the model does not diverge and provides momentum enhancement values of the same order of magnitude as for radii within the validity range. These potential model inaccuracies are acknowledged in this study but are not expected to compromise the validity of the analysis in Section 6.2. Furthermore, as shown in Section 5.4, particles larger than 0.35 – 0.75 mm (10^{-7} – 10^{-6} kg) are already expected to produce attitude errors larger than

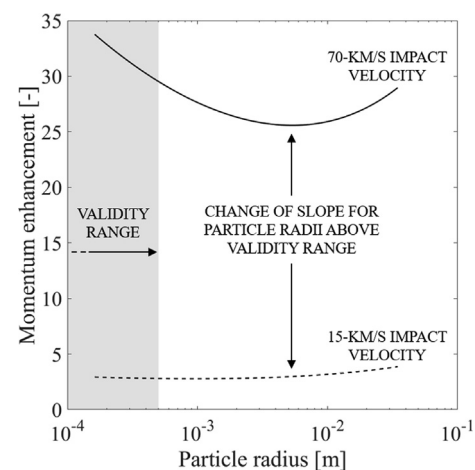


Fig. 10. Momentum enhancement due to hypervelocity impacts as a function of impactor radius.

the requirements of the narrow-angle camera, and even larger particles may result in tumbling of the spacecraft or even critical internal damage. Thus, inaccuracies in the modeling of large particle impacts become less compromising to the validity of the attitude performance analysis.

The employed model for hypervelocity impacts therefore provides a mathematical expression for the linear momentum of ejecta generated after the impact, $\mathbf{p}_e^{(+)}$, based on known quantities such as the kinetic energy of the impacted particle, incidence angle, and impacted material. The total transfer of linear momentum is then simply $\mathbf{p}_p^{(-)} - \mathbf{p}_e^{(+)}$: i.e., difference between the relative linear momentum of the impacted particle before the impact, $\mathbf{p}_p^{(-)} = m_p \mathbf{v}_p$, and the linear momentum of the generated ejecta. An expression for the total angular momentum transfer can also be obtained from the conservation of angular momentum before and after the impact, since no external torques are exerted on the system.

A spacecraft-particle system can be defined before the impact, with angular momentum $\mathbf{H}_{SC+p}^{(-)}$, and a spacecraft-ejecta system can be defined after the impact, with angular momentum $\mathbf{H}_{SC+e}^{(+)}$. The conservation of angular momentum through an impact can then be expressed in the inertial reference frame and relative to CM as in Eq. (9).

$$\begin{aligned} \mathbf{H}_{SC+p}^{(-)} &= {}^B \underline{\mathbf{C}}^I \left(\underline{\mathbf{J}}_T \boldsymbol{\omega}^{B(-)} + {}^w \underline{\mathbf{A}}^B \underline{\mathbf{J}}_w \boldsymbol{\Omega}_w^{(-)} \right) + \mathbf{r}_p^{CM} \times \mathbf{p}_p^{(-)} \\ &= {}^B \underline{\mathbf{C}}^I \left(\underline{\mathbf{J}}_T \boldsymbol{\omega}^{B(+)} + {}^w \underline{\mathbf{A}}^B \underline{\mathbf{J}}_w \boldsymbol{\Omega}_w^{(+)} \right) + \mathbf{r}_p^{CM} \times \mathbf{p}_e^{(+)} \\ &= \mathbf{H}_{SC+e}^{(+)} \end{aligned} \quad (9)$$

where ${}^B \underline{\mathbf{C}}^I$ is the rotation matrix from the body-fixed to the inertial reference frame. By assuming reaction wheels are unperturbed through the impact: $\boldsymbol{\Omega}_w^{(-)} = \boldsymbol{\Omega}_w^{(+)}$ (i.e., angular momentum is transferred fully into the spacecraft), one may then compute the resulting change in spacecraft angular velocity $\Delta \boldsymbol{\omega}^B = \boldsymbol{\omega}^{B(+)} - \boldsymbol{\omega}^{B(-)}$ from Eq. (9). Such change in angular velocity is assumed to occur instantaneously, and it models the attitude perturbation due to a particle impact at time t_p . The same expression is applied when modeling perfectly plastic impacts, but simply substituting $\mathbf{p}_e^{(+)} = \mathbf{0}$ as no ejecta is generated in such cases.

Note that the transfer of linear momentum due to particle impacts, $\mathbf{p}_p^{(-)} - \mathbf{p}_e^{(+)}$, is neglected in this study, since the resulting change in spacecraft velocity, $\Delta \mathbf{v}_r = |\mathbf{p}_p^{(-)} - \mathbf{p}_e^{(+)}|/m_{SC}$, is several orders of magnitude smaller than the fly-by speed v_r . For reference, a 1-gram particle would cause a change in velocity of up to 15 m/s (for a maximum fly-by speed of 70 km/s), which is more than 3 orders of magnitude smaller than v_r , and these impacts are highly unlikely as shown in Section 5.3. Similarly, more common particles (e.g., 10^{-8} – 10^{-6} kg) result in changes in velocity 6 to 8 orders of magnitude smaller

than v_r , and only a few tens of them are expected to be encountered (Section 5.3).

5. Pre-analysis considerations and characterization of the problem

Monte Carlo simulations are performed in Section 6 to characterize the behavior of the attitude control system through the widely uncertain environment to be encountered in the actual mission. To model the stochasticity of the problem, different fly-by conditions and distributions of the dust environment are generated for each Monte Carlo case (Section 5.1). Attitude control gains are also selected taking into consideration the uncertainty of the dust environment (Section 5.2), and initial characterization of the problem is provided by Sections 5.3, 5.4 and 5.5.

5.1. Setup of Monte Carlo analysis

As a first step, the trajectory of the spacecraft is defined by an initial position on the $\hat{\mathbf{c}}_x$ - $\hat{\mathbf{v}}_r$ plane: $\mathbf{r}_{SC}(t=0) = h_f \hat{\mathbf{c}}_x + y_0 \hat{\mathbf{v}}_r$, and a relative fly-by speed $\mathbf{v}_r = v_r \hat{\mathbf{v}}_r$. The relative fly-by speed v_r is randomly generated in each Monte Carlo case according to the distribution in Fig. 6. The fly-by altitude h_f is also an uncertain quantity with expected normal distribution 750 ± 250 km (1σ). A total of nine discrete, deterministic possibilities for h_f are studied: $h_f \in [150 + 150i]$ km for $i \in [0, 8]$, and a total of 10,000 Monte Carlo simulations are run for each of these fly-by altitudes. Analysis of discrete h_f values allows to characterize the attitude performance as a function of fly-by altitude, and the statistics of the stochastic problem can be approximated by weighing the deterministic cases according to the probability density function of h_f 's normal distribution. For each of these fly-by altitudes, the initial $\hat{\mathbf{v}}_r$ -coordinate of the spacecraft relative to the comet y_0 is computed from $d_0 = \sqrt{h_f^2 + y_0^2}$, where $d_0 = 50,000$ km is the first and farthest data point in the vector $d_k \in [0, N-1]$ provided by the EDCM (Section 3.1). This fully defines the spacecraft's initial position and velocity vectors $\mathbf{r}_{SC}$ and $\mathbf{v}_r$ for each Monte Carlo simulation, with an initial orientation equal to the desired inertially-fixed orientation: $\mathbf{q}_{SC}(t=0) = \mathbf{q}_e$, and zero angular velocity: $\boldsymbol{\omega}(t=0) = \mathbf{0}$. Note that reaction wheels are also assumed to be initially unloaded: $\boldsymbol{\Omega}_w = \mathbf{0}$, since no improvement is observed when reaction wheels are pre-loaded (Section 6.1).

For each fly-by altitude h_f , the EDCM is adapted as described in Section 3.2 to place particles of various masses along the several subdivisions $[d_k, d_{k+1}]$ of the fly-by trajectory, for a given percentile of the dust environment density. Note that the position of dust particles $\mathbf{r}_p$ is randomized for each individual Monte Carlo case. Dust environment density is an uncertainty quantity, and a total of 100 discrete, deterministic environment density percentiles are considered for each fly-by altitude (equally spaced between the 1st and the 99th percentiles). Then, 100 Monte Carlo sim-

ulations are performed for each of these discrete percentiles, amounting for a total of $100 \times 100 = 10,000$ Monte Carlo simulations for each fly-by altitude. Since a uniform discretization of density percentiles is employed, each of the 10,000 Monte Carlo simulations also has equal probability of occurring during the real mission, and this fact is leveraged to recover the statistics of the stochastic problem.

Once the initial state of the spacecraft is defined and the dust environment is generated for each Monte Carlo case, simulations can be run. Note now that, if the narrow-angle camera has a full angle of view of $\text{FOV}_x = 2.6^\circ$ on the body-fixed $\hat{x}^B\text{--}\hat{y}^B$ plane (JAXA Comet Interceptor Team, 2021), under nominal circumstances (i.e., with no pointing errors), the comet will only be within the field of view of the camera when the spacecraft is between $\hat{v}_r$ -coordinates $-\tan(\text{FOV}_x/2)h_f$ and $+\tan(\text{FOV}_x/2)h_f$. As such, from each Monte Carlo simulation, attitude performance indicators such as mean and maximum pointing errors or angular velocities are recorded within the nominal observation window, and simulations are finally stopped when the spacecraft reaches $\hat{v}_r$ -coordinate $+\tan(\text{FOV}_x/2)h_f$ (i.e., when the comet nominally leaves the field of view). Results from all Monte Carlo simulations are then summarized in the form of percentiles.

5.2. Selection of attitude control gains

Several observations are made in the process of selecting control gains k (proportional gain) and c (derivative gain). Firstly, an order of magnitude for control gains is inferred from the narrow-angle camera requirements and specifications of the reaction wheels: $[k] \sim [T_{w,lim}]/[\varepsilon_{req}]$ and $[c] \sim [T_{w,lim}]/[\omega_{req}]$. Recall that reactions wheels can generate a maximum torque $T_{w,lim} = 25 \text{ mN} \cdot \text{m}$, and the attitude requirements are $\varepsilon_{req} = 0.5^\circ$ in pointing error and $\omega_{req} = 0.4 \text{ deg/s}$ in angular velocity. The expected orders of magnitude of control gains are then $[k] \sim 2.9 \text{ N} \cdot \text{m/rad}$ and $[c] \sim 3.6 \text{ N} \cdot \text{m} \cdot \text{s/rad}$.

Secondly, it is noticed that the uncertainty in the encountered dust environment does not allow for a traditional selection of control gains. Each single selection of control gains results in a range of different pointing errors and angular velocities depending on the density of the dust environment, on the impact position relative to the center of mass, and on the location of the particles along the fly-by trajectory. As such, a grid-search parametric study is combined here with a Monte Carlo analysis to incorporate the dependency of attitude performance on the dust environment, and control gains resulting in the averagely best attitude performance are selected.

A grid of 30×30 combinations of k and c is generated, uniformly distributed in a logarithmic scale over the $10^{-1}\text{--}10^1 \text{ N} \cdot \text{m/rad}$ and $10^{-1}\text{--}10^1 \text{ N} \cdot \text{m} \cdot \text{s/rad}$ ranges (according to their expected orders of magnitude), and the

performance of each combination is tested for the same 200 dust environments generated as described in Section 5.1, for a fixed fly-by altitude of 250 km (2σ lower bound), and fixed 90th-percentile dust environment density: to focus only on dust environments with a rather homogeneous distribution of particles, since lower-density environments (with more sparse distribution of particles) provide inconsistent information on attitude performance. Quantities such as mean pointing error ε_{mean} , maximum pointing error ε_{max} , and mean angular velocity ω_{mean} within the nominal observation window are stored from these simulations, together with the average generated torque T_{mean} throughout the whole simulated trajectory: i.e., between $\hat{v}_r$ -coordinates y_0 and $\tan(\text{FOV}_x/2)h_f$.

As a summary of this parametric study, Fig. 11 illustrates the attitude performance (averaged over 200 Monte Carlo cases) resulting from each combination of gains k and c .

Four distinct regions can be observed in Fig. 11 (labeled):

- 1) Small values of k and c , which result in low overall performance due to insufficient generated torque T_{mean} .
- 2) Large k and small c , which result in reasonable average pointing error ε_{mean} , but inconsistent ω_{mean} performance and largest generated torques.
- 3) Small k and large c , which result in large pointing errors ε_{mean} and angular velocities ω_{mean} .
- 4) k and c in the order of $\log_{10} 0 = 1$, which result in the best overall performances by means of reasonable values of T_{mean} .

Also indicated in Fig. 11 (black outlined square) are the selected control gains $k = 1.5 \text{ N} \cdot \text{m/rad}$ and

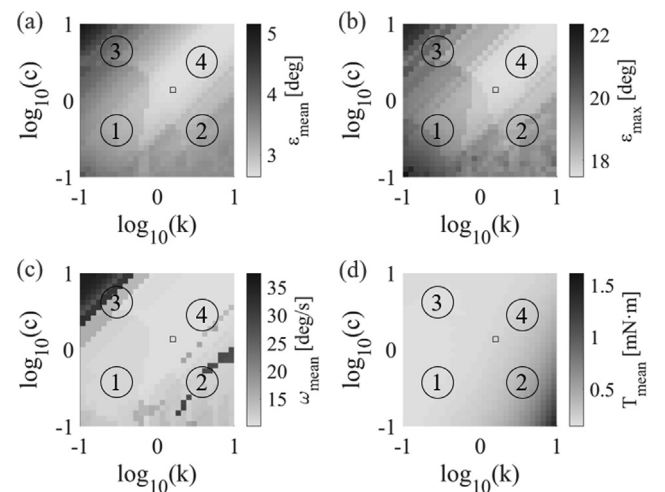


Fig. 11. Effect of control gains on (a) mean pointing error, (b) maximum pointing error, (c) mean angular velocity, and mean generated torque (average over 200 Monte Carlo runs, 250-km fly-by and 90th-percentile dust environment density).

$c = 1.3 \text{ N} \cdot \text{m} \cdot \text{s}/\text{rad}$ employed in the remaining of this study. Such gains are centered within region 4, although their specific values are arbitrarily selected within this region since it presents a rather homogeneous performance.

5.3. Characterization of dust environment

The procedure described in Section 3.2 to adapt the EDCM and randomize dust environments is used here to characterize the number of particles that can be expected along fly-by trajectories. Notice that the number of encountered particles depends on the cross-sectional area that is exposed to the dust environment A_{SC} , and so, for reference, it is simply assumed here that A_{SC} corresponds to that of the nominal orientation of the spacecraft $\mathbf{q}_{SC} = \mathbf{q}_c$: $A_{SC} = 0.4 \cdot 0.2 \text{ m}^2$ (recall that solar arrays are assumed to have zero thickness). Table 2 then summarizes the expected number of particles along the simulated fly-by trajectories: i.e., between $\hat{\mathbf{v}}_r$ -coordinates y_0 and $+\tan(\text{FOV}_x/2)h_f$, for mass decades between 10^{-11} and 10^{-1} kg , and for various fly-by altitudes and dust environment densities.

The preliminary observations stated in Section 3.1 still hold when looking at Table 2, and, more specifically, it is now observed that smaller particles are more numerous, with increments of approximately one order of magnitude every mass decade. Further, the uncertainty in number of particles (i.e., range between low and high percentiles) is more prominent for large particles: the uncertainty for small particles is of approximately one order of magnitude, and of approximately three orders of magnitudes for large particles. Table 2 also shows that from a few to thousands of small particles can be expected (10^{-11} – 10^{-8} kg), less than one to tens of particles of 10^{-5} – 10^{-8} kg may be encountered, and larger particles become more unlikely: e.g., 0.0038 particles of mass 10^{-2} – 10^{-1} kg are expected along a 250-km fly-by (90th percentile), which means that, in the best 90% of the cases, the probability of encountering one of these particles along a 250-km fly-by is lower than 0.38%.

5.4. Characterization of single particle impacts

Evaluation of single particle impacts can provide an insight into attitude perturbation as a function of particle mass. For a testcase scenario in which the initial orientation is equal to the desired orientation: $\mathbf{q}_{SC} = \mathbf{q}_c$, single particle impacts are assumed to occur at the farthest possible point from the center of mass on the bumper face: $\mathbf{r}_{p,max}^{CM} = 0.15\hat{\mathbf{x}}^B \pm 0.2\hat{\mathbf{y}}^B \pm 0.1\hat{\mathbf{z}}^B$. Such an impact will generate the largest possible perturbation in angular velocity $\Delta\omega$ for a given particle mass m_p , assuming that solar arrays have zero thickness and so they may not be impacted when $\mathbf{q}_{SC} = \mathbf{q}_c$. Notice also that, under this configuration, the specific quadrant of $\mathbf{r}_{p,max}^{CM}$ does not affect the magnitude of the attitude perturbation due to the symmetry of the problem.

As an initial example, for an impact particle of mass $2.5 \cdot 10^{-7} \text{ kg}$ and impact speed of 70 km/s, Fig. 12 illustrates the magnitude of the angular velocity ω and the pointing error $\varepsilon = |2 \cdot \tan^{-1}(|q_{e1}, q_{e2}, q_{e3}|/q_{e4})|$ as a function of time. It is initially observed that component inaccuracies induce a baseline attitude error, below $\varepsilon = 0.01^\circ$ and $\omega = 0.01 \text{ deg/s}$, even if no particles are impacted. After impact, the pointing error rapidly increases due to the sudden change in angular velocity $\Delta\omega = 0.34 \text{ deg/s}$, which is then corrected by the controller. In particular, the pointing error reaches a maximum of $\varepsilon_{max} = 0.10^\circ$ prior to being mitigated by the controller, and the maximum angular velocity, $\omega_{max} = \Delta\omega$, is registered at the time of impact.

In an effort to characterize the effect of single particle impacts as a function of mass, similar simulations to that in Fig. 12 are performed for particles of mass 10^{-11} – 10^{-1} kg , and for impact velocities of 15 and 70 km/s. The maximum pointing error ε_{max} and maximum angular velocity ω_{max} resulting from each simulation are illustrated in Fig. 13.

It is initially observed in Fig. 13 that, due to component inaccuracies, the effect of particles of up to 10^{-8} – 10^{-7} kg is not perceptible: the baseline noise induced by component

Table 2
Expected number of particles along simulated trajectory for various fly-by altitudes and dust environment densities.

Particle mass (kg)	Fly-by altitude								
	250 km			750 km			1350 km		
	10th perc.	50th perc.	90th perc.	10th perc.	50th perc.	90th perc.	10th perc.	50th perc.	90th perc.
10^{-2} – 10^{-1}	$3.0 \cdot 10^{-6}$	0.0001	0.0038	$9.9 \cdot 10^{-7}$	$3.7 \cdot 10^{-5}$	0.0013	$5.5 \cdot 10^{-7}$	$2.0 \cdot 10^{-5}$	0.0007
10^{-3} – 10^{-2}	$2.8 \cdot 10^{-5}$	0.0008	0.0185	$9.1 \cdot 10^{-6}$	0.0002	0.0061	$5.0 \cdot 10^{-6}$	0.0001	0.0033
10^{-4} – 10^{-3}	0.0003	0.0052	0.0925	0.0001	0.0016	0.0295	$4.5 \cdot 10^{-5}$	0.0009	0.0163
10^{-5} – 10^{-4}	0.0023	0.0340	0.4716	0.0007	0.0109	0.1497	0.0004	0.0060	0.0821
10^{-6} – 10^{-5}	0.0206	0.2275	2.4170	0.0066	0.0732	0.7681	0.0036	0.0407	0.4197
10^{-7} – 10^{-6}	0.1886	1.5966	12.422	0.0604	0.5076	3.9692	0.0332	0.2818	2.2025
10^{-8} – 10^{-7}	1.6894	11.129	67.383	0.5434	3.5526	21.364	0.2984	1.9653	11.812
10^{-9} – 10^{-8}	14.929	78.122	372.05	4.8052	25.039	117.20	2.6452	13.817	64.654
10^{-10} – 10^{-9}	128.96	557.25	2097.2	41.203	178.31	661.08	22.893	98.508	366.90
10^{-11} – 10^{-10}	1118.6	4075.8	12336	355.55	1296.7	3916.2	197.15	715.39	2172.6

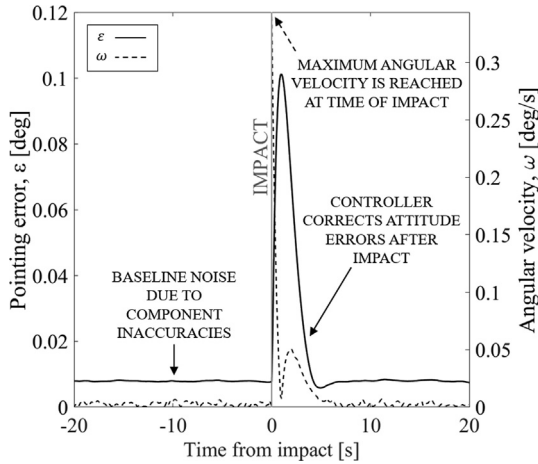


Fig. 12. Pointing and angular velocity error due to impact particle of mass $2.5 \cdot 10^{-7}$ kg at 70 km/s.

inaccuracies is larger than the attitude perturbation produced by impact particles. Through Fig. 13, it is also clear that the pointing requirement ε_{req} is exceeded if particles larger than 10^{-6} – 10^{-5} kg are impacted, and the angular velocity requirement ω_{req} is exceeded for particle masses above 10^{-7} – 10^{-6} kg. Notice also the change in slope of ε_{max} at 10^{-6} – 10^{-5} kg, which corresponds to torque requirements exceeding the capability of the reaction wheels. The behavior of ε_{max} also changes above 10^{-5} kg, corresponding to a tumbling spacecraft with rather unpredictable attitude performance. Lastly, it is observed that the angular velocity follows a linear trend as a function of particle mass, which can already be inferred from Eq. (9), and this maximum angular velocity is registered at the time of impact, as shown in Fig. 12.

In summary, it is shown that the attitude of the spacecraft is highly sensitive to particle impacts (due to high impact velocities), even for particle masses in the 10^{-7} – 10^{-6} -kg range—of which a few up to a dozen of them

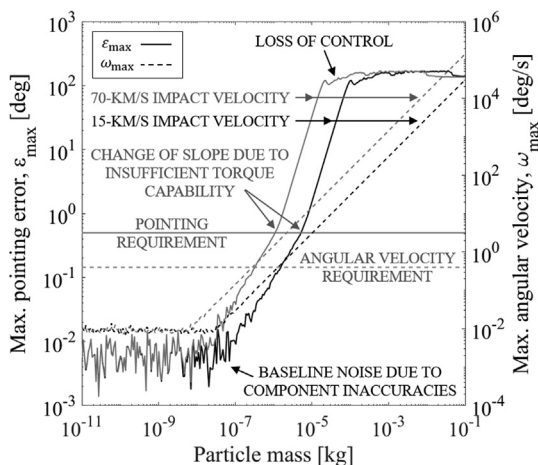


Fig. 13. Maximum pointing error and angular velocity as a function of particle mass.

are expected to be encountered (Section 5.3). Moreover, single impacts of smaller particles (10^{-11} – 10^{-7} kg) generate errors within the requirements of the mission, but it shall still be assessed whether multiple impacts of these (more numerous) smaller particles can result in significant attitude errors (Section 5.5).

5.5. Characterization of multiple impacts of similar mass

The effect of multiple impacts of similar mass is characterized here by performing simulations that include particles belonging to only one mass decade at a time: e.g., including particles of mass 10^{-10} – 10^{-9} kg only, or particles of mass 10^{-9} – 10^{-8} kg, etc. One simulation is performed for each mass decade in a worst-case type of scenario: with a fly-by velocity of 70 km/s (upper limit), a fly-by altitude of 250 km (2σ lower bound), and a 99th-percentile dust environment density, and particles are generated and randomly distributed along the fly-by trajectory as described in Section 5.1. Results from such simulations may be treated as an approximated upper limit to the perturbation generated by particles of similar mass, although results may vary for different spatial distributions of particles, or could be even worse if the fly-by altitude falls beyond the 2σ interval or if cloud-like regions are encountered during the actual mission (not modeled here).

As an example, Fig. 14 illustrates the effect of 10^{-7} – 10^{-6} -kg particle impacts on the pointing error, where the dotted vertical lines indicate the times at which impacts occur. It can be observed that the pointing error ε due to particles of mass 10^{-7} – 10^{-6} kg accumulates as the concentration of particles in close proximity to the comet increases. A maximum pointing error of 1.09 degrees is registered, but, given the spatial distribution of particles, this maximum value is reached prior to the observation window (which lasts less than 0.2 s due to the 70-km/s fly-by speed, and is indicated as a thin, shadowed area in Fig. 14). The

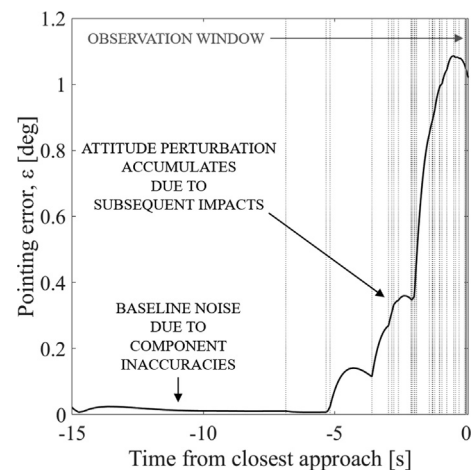


Fig. 14. Pointing error due to impacts of 10^{-7} – 10^{-6} -kg particles only (70 km/s, 250-km fly-by, and 99th-percentile dust environment density).

maximum pointing error within the observation window is 1.06 degrees in this case.

In an effort to characterize the effect of multiple impacts of particles of similar mass, Table 3 then summarizes the maximum pointing and angular velocity errors ε_{max} and ω_{max} generated by particles of mass from 10^{-10} kg to 10^{-4} kg. Since maximum attitude errors may or may not occur within the observation window, depending on the distribution of particles, Table 3 presents the maximum errors throughout the simulated trajectory (instead of within the observation window), to provide estimates of the worst-case, maximum effect of particles of similar mass.

Various observations can be drawn from Table 3:

- Particles of mass 10^{-5} – 10^{-4} kg can result in angular velocities above 100 deg/s, which effectively correspond to a tumbling spacecraft whose attitude is unlikely to be recovered during the fly-by. For reference, there is almost a 50% probability of encountering one of these particles along a 250-km fly-by and a 90th-percentile environment density (Table 2), but this probability is smaller for larger fly-by altitudes and lower dust environment densities.
- The errors induced by particles of mass 10^{-8} – 10^{-5} kg may be larger than requirements ε_{req} and ω_{req} by almost one order of magnitude. From a few up to several tens of these particles are expected along a 250-km fly-by and a 90th-percentile environment density (Table 2). These particles are expected to be less common for larger fly-by altitudes and lower environment densities, but their perturbation still represents one of the main sources of attitude error.
- Particles smaller than 10^{-8} kg generate errors that remain more than one order of magnitude below the requirements of the mission. From a few hundreds to thousands of these particles may be encountered along a 250-km fly-by (90th percentile), and their perturbation effectively induces attitude jitter throughout the trajectory, similar to and of the same order of magnitude as component inaccuracies. Jitter stability is relevant to image acquisition and shall be taken into account by the Science Team. Note, however, that these particles are neglected in the Monte Carlo analysis in Section 6 (to lower the computational cost of simulating numerous impacts), since their perturbation is significantly

below mission requirements even for a 250-km fly-by, and this perturbation is also much smaller than that induced by the also frequent 10^{-8} – 10^{-5} -kg particles.

6. Analysis and recommendations

Once the effect of single particles impacts and of particles of similar mass is characterized, a full Monte Carlo analysis is performed in the current section. Particles in the 10^{-8} – 10^{-1} -kg mass range are considered in this analysis (according to conclusions in Sections 5.3, 5.4 and 5.5), and dust environments are randomized as described in Section 5.1. Several scenarios are studied in the current section, which allow to provide a comprehensive understanding of the effect of various mission and environment factors. The mission scenarios studied here are: (1) baseline mission scenario: with perfectly aligned solar arrays, no momentum enhancement, and initially unloaded RWP500 reaction wheels (Section 6.1), (2) baseline mission scenario with momentum enhancement (Section 6.2), (3) baseline mission scenario with misaligned solar arrays (Section 6.3), and (4) baseline mission scenario with upgraded reaction wheel along the camera line-of-sight (Section 6.4).

6.1. Performance through baseline mission scenario

The attitude performance through randomized dust environments can initially be analyzed as a function of fly-by altitude. Quantities such as mean and maximum pointing errors, ε_{mean} and ε_{max} , and mean and maximum angular velocity, ω_{mean} and ω_{max} , within the nominal observation window are summarized in Table 4, as well as the length of time that the target comet remains within the narrow-angle camera field of view (expressed as a percentage of the nominal observation time $2 \cdot \tan\left(\text{FOV}_x/2\right)h_f/v_r$). The last column in Table 4 summarizes the maximum angular momentum of the reaction wheel that is aligned with the camera line-of-sight throughout the simulated trajectory, $H_{w,max}$, expressed as a percentage of the maximum angular momentum that can be generated by reaction wheels, $H_{w,lim}$.

It can initially be observed in Table 4 that pointing and angular velocity requirements $\varepsilon_{req} = 0.5^\circ$ and $\omega_{req} = 0.4$ deg/s can only be fulfilled by more than 95% of the cases if the fly-by altitude is 1050 km or above. Further, it is seen that more than 90% of the cases can fulfill narrow-angle camera requirements if the fly-by altitude is 600 km or above. As a general trend, it can also be observed that pointing requirements are more likely to be fulfilled than angular velocity requirements, and, as a more intuitive observation, attitude performance improves for larger fly-by altitudes where dust environment density is lower. It may also be worth mentioning that (although these results are omitted for lack of relevance) 99th percentiles result in a tumbling spacecraft with zero observa-

Table 3

Attitude error due to multiple impacts of similar mass (70 km/s, 250-km fly-by, and 99th-percentile dust environment density).

Particle mass (kg)	ε_{max} (deg)	ω_{max} (deg/s)
10^{-5} – 10^{-4}	26.43	114.3
10^{-6} – 10^{-5}	1.156	2.880
10^{-7} – 10^{-6}	1.086	1.478
10^{-8} – 10^{-7}	0.169	0.261
10^{-9} – 10^{-8}	0.027	0.033
10^{-10} – 10^{-9}	0.012	0.013

Table 4
Attitude performance for various fly-by altitudes.

Altitude	Percentile	$\varepsilon_{mean}(\text{deg})$	$\varepsilon_{max}(\text{deg})$	Time within FOV (%)	$\omega_{mean}(\text{deg/s})$	$\omega_{max}(\text{deg/s})$	$H_{w,max}(\% \text{ of } H_{w,lim})$
450 km	50th	0.010	0.011	99.50	0.007	0.011	0.311
	75th	0.042	0.051	98.53	0.048	0.074	2.147
	90th	0.462	0.575	82.14	0.610	0.967	11.52
	95th	11.21	12.56	0.000	7.408	8.552	25.65
600 km	50th	0.008	0.009	100.0	0.005	0.008	0.256
	75th	0.021	0.026	99.46	0.023	0.040	1.386
	90th	0.167	0.208	94.09	0.195	0.351	8.444
	95th	2.680	3.462	3.121	2.648	3.568	22.22
750 km	50th	0.008	0.008	100.0	0.004	0.007	0.236
	75th	0.014	0.017	99.48	0.014	0.026	1.128
	90th	0.090	0.116	97.28	0.100	0.183	6.236
	95th	0.577	0.779	79.61	0.770	1.387	17.83
900 km	50th	0.007	0.008	100.0	0.004	0.006	0.228
	75th	0.012	0.013	99.49	0.009	0.017	0.814
	90th	0.045	0.061	98.47	0.048	0.093	4.303
	95th	0.175	0.231	93.43	0.208	0.489	12.53
1050 km	50th	0.007	0.007	100.0	0.003	0.006	0.214
	75th	0.011	0.012	99.49	0.007	0.013	0.653
	90th	0.032	0.045	99.32	0.037	0.072	3.678
	95th	0.127	0.170	95.38	0.133	0.296	10.78

tion times and angular velocities of tens or hundreds of degrees per second. Lastly, it is observed that reaction wheel saturation is not reached given the short duration of fly-by trajectories, and, as expected, larger values of angular momentum $H_{w,max}$ are reached at low fly-by altitudes where the dust environment density is higher. Loading values of up to 26% are reached at 450 km (95th percentile), and these values increase up to 28% at lower fly-by altitudes. It is worth highlighting that authors observed no significant improvement in attitude performance when the reaction wheel aligned with the camera line-of-sight was pre-loaded 72% of the available $H_{w,lim}$ (i.e., unused angular momentum) prior to the fly-by: pointing error's 95th percentile improved from 8% to 21% observation times, but a detriment in lower-percentile attitude performance is observed due to an increase in the perturbing torque $T_{w,p}$ (Eq. (7)).

Once the problem is discussed for deterministic fly-by altitudes, the overall attitude performance of the stochastic problem (i.e., with uncertain fly-by altitude) can also be analyzed. Table 5 then shows that, for the baseline mission scenario, more than 90% of the cases can be expected to fulfill narrow-angle camera requirements, and this equates into maintaining the target comet within FOV for more than 95% of the nominal observation time. Less than 10% of the cases, however, are not expected to fulfill atti-

tude requirements due to high dust environment densities and/or low fly-by altitudes. Similarly, less than 5% of cases would result in a tumbling spacecraft with zero observation times and large angular velocities.

It is worth recalling now that the attitude determination process may face difficulties due to cometary dust particles within the field of view of the star tracker, unless robust star tracker software is developed or gyroscopes are leveraged instead. Authors observed that attitude knowledge inaccuracies larger than those baselined in Section 4.2 affect most prominently the lower-percentile performances (i.e., 50th and 75th percentiles), whose values are primarily driven by component inaccuracies, whereas larger percentiles (i.e., 90th and 95th) are mainly driven by dust particle impacts. For reference, attitude knowledge inaccuracies ten times larger than those in Section 4.2 (i.e., 60 arcsec = 0.02 deg and 400 arcsec = 0.1 deg bore-sight and cross-bore-sight standard deviations) would result in 10–20% larger 50th-percentile pointing errors and increments below 5% in 75th-percentile pointing errors. Note that the 90th and 95th percentiles would remain unaltered and so would the probabilities of fulfilling pointing error and angular velocity requirements. Interestingly, however, large angular velocities would be induced as a result of trying to correct such large cross-bore-sight inaccuracies: 0.1 deg (1 σ). These angular velocities may be two to seven

Table 5
Overall attitude performance for baseline mission scenario.

Percentile	$\varepsilon_{mean}(\text{deg})$	$\varepsilon_{max}(\text{deg})$	Time within FOV (%)	$\omega_{mean}(\text{deg/s})$	$\omega_{max}(\text{deg/s})$
50th	0.008	0.008	100.0	0.004	0.007
75th	0.017	0.021	99.47	0.018	0.032
90th	0.144	0.172	95.29	0.165	0.276
95th	2.398	2.905	7.987	2.478	3.266

times larger than the baseline performance in Table 5, but they could be avoided by redefining the control law in Eq. (5) and correcting boresight pointing errors only: i.e., neglecting cross-boresight pointing errors which would effectively result in different orientations of the collected images of the target comet. Similarly, attitude knowledge inaccuracies even one hundred times larger than the baseline star tracker specifications would result in two to five times larger 50th- and 75th-percentile pointing errors (90th and 95th percentiles would still remain unaffected), and, in this case, even the 50th-percentile angular velocity performance would be beyond ω_{req} (unless the control law is modified). Conclusively, if attitude determination performance is affected by the severity of the environment, it is foreseen that larger knowledge inaccuracies will worsen lower-percentile attitude performance, but the probability of fulfilling pointing error requirements would not be reduced even with inaccuracies two orders of magnitude larger than those baselined in Section 4.2.

6.2. Performance with momentum enhancement

The effect of momentum enhancement due to hypervelocity impacts (Section 4.2.2) can then be observed by comparing results in Table 6 to those of the baseline mission scenario (Table 5), which assumes perfectly plastic impacts.

An attitude performance detriment of approximately a factor of three is observed in the 95th-percentile results (which were already beyond attitude requirements in Section 6.1), but it should be noticed that more than 90% of the cases are still expected to fulfill camera requirements even when considering momentum enhancement. This 90th-percentile performance presents errors approximately 25% higher than those in Table 5, whereas lower-percentile errors remain nearly the same. It is thus argued that modeling the momentum enhancement of hypervelocity impacts is not essential to the validity of the analysis and to estimations of probability of success. The modeling of such impacts becomes most relevant when attitude errors are beyond camera requirements and impacts on faces other than the bumper become more frequent.

6.3. Performance with misaligned solar arrays

Best attitude performance is expected with solar arrays perfectly aligned with the incoming flow of particles: i.e., with normal vectors perpendicular to the relative fly-by velocity $\mathbf{v}_r$; however, mechanical imprecisions in the orientation of solar arrays may result in particle impacts farther

away from the center of mass of the spacecraft even if the spacecraft is oriented as desired: $\mathbf{q}_{SC} = \mathbf{q}_c$. The effect of such potential misalignments is analyzed in this section. Two testcase scenarios are considered, in which both solar arrays are rotated either one or five degrees about the body-fixed $\hat{\mathbf{z}}^B$ axis. Both solar arrays are conservatively rotated in the same direction so that the effect of impacts about the $\hat{\mathbf{z}}^B$ axis is accumulated rather than compensated (see Fig. 15). Attitude performance under such scenarios is summarized in Table 7. It is also worth noting that a misalignment of one degree results in an additional area exposed to the dust environment equivalent to almost twice the lateral area of solar arrays (which is neglected when assuming that solar arrays have zero thickness). As such, the one-degree misalignment results in Table 7 can also be used to conservatively assess the validity of such an assumption.

On the one hand, it is observed that a 1-deg misalignment of solar arrays results in 40% worse 95th-percentile pointing errors, 35% worse 95th-percentile angular velocities, and zero observation times. Further, the 90th-percentile pointing errors are approximately 15% larger than with perfectly aligned solar arrays, angular velocities are 40% larger, and observations times are reduced 0.6%. Lower-percentile performances show no difference in pointing error, and a detriment of 20% is observed in angular velocity. It is thus argued that misalignments of solar arrays as small as one degree can have significant effect especially on 95th-percentile performance, whereas 90th-percentile errors still fulfill attitude requirements and observation times are preserved. The modeling errors associated to solar arrays having a zero thickness can be expected to be smaller (approximately half) than those induced by a 1-deg misalignment, and so conclusions on 90th-percentile (or lower) performance, observation times, and fulfillment of narrow-angle camera requirements are argued to be valid for the scope of this research, especially in the context of other large sources of uncertainty such as dust environment (spatial density and distribution), fly-by altitude, momentum enhancement, solar array misalignment, perforation of spacecraft surfaces, etc.

On the other hand, a 5-deg solar array misalignment results in 2–4 times larger 95th-percentile errors and zero observation times, and 90th-percentile errors are also worsened by a factor of 0.5 (pointing error) and 5 (angular velocity). It is worth noticing that angular velocities are again more highly perturbed than pointing errors, since the magnitude of attitude perturbation $\Delta\omega$ (larger for impacts farther away from the CM) proportionally affects

Table 6
Overall attitude performance with momentum enhancement.

Percentile	$\varepsilon_{mean}(\text{deg})$	$\varepsilon_{max}(\text{deg})$	Time within FOV (%)	$\omega_{mean}(\text{deg/s})$	$\omega_{max}(\text{deg/s})$
50th	0.008	0.008	100.0	0.004	0.007
75th	0.017	0.021	99.47	0.017	0.031
90th	0.154	0.206	95.08	0.188	0.354
95th	8.149	9.213	0.000	7.682	9.456

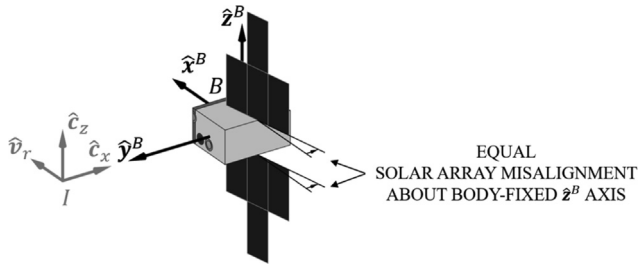


Fig. 15. Spacecraft configuration with misaligned solar arrays.

the angular velocity error, whereas pointing errors correspond to the integrated effect of this attitude perturbation (lessened by the controller). As a consequence, 90th-percentile pointing errors still remain below ε_{req} , but angular velocities exceed camera requirements. Lastly, it is seen that more than 75% of the cases do fulfill attitude requirements even with a 5-deg solar array misalignment, although angular velocity errors increase by a factor of 2.5 compared to those in Table 5, and pointing errors worsen 10%. Conclusively, proper alignment of solar arrays parallel to the incoming flow of particles is crucial to fulfilling attitude requirements, since small misalignments (less than 5 degrees) can significantly increase attitude errors—especially on angular velocity—and they may compromise 90th-percentile performance.

6.4. Performance with upgraded reaction wheel

In an effort to explore potential solutions for improved attitude performance, two alternative scenarios are consid-

ered in which the reaction wheel aligned with the camera line-of-sight has either (1) a larger torque capability ($T_{w,lim} = 70 \text{ mN} \cdot \text{m}$), or (2) larger torque and angular momentum capabilities ($T_{w,lim} = 70 \text{ mN} \cdot \text{m}$ and $H_{w,lim} = 1 \text{ N} \cdot \text{m} \cdot \text{s}$). This second scenario is equivalent to incorporating the larger Blue Canyon Technologies' RW1 reaction wheel, instead of RWP500, along the camera line-of-sight (Blue Canyon Technologies, 2021). Results from both scenarios are summarized in Table 8.

In both scenarios, performance improvements are observed throughout all percentiles, and these improvements are most notable for larger percentiles: 90th percentiles improve $\sim 5\%$ and 95th percentiles improve 10–30%; however, 95th-percentile performance still remains beyond narrow-angle camera requirements. More specifically, with a larger torque capability, 95th-percentile angular velocities improve approximately 30%, and pointing errors improve 10%, which then results in an increment of 15% in observation times (i.e., 23% instead of 8%). With a larger reaction wheel, 95th-percentile pointing errors improve approximately 10% as well, but this increases observation times a 20% instead, since ε_{mean} and ω_{mean} performances are slightly better: this translates into maintaining the comet within the field of view up to 27% of the nominal observation time (instead of 8%). In summary, potential upgrades in the reaction wheel that is aligned with the camera line-of-sight can improve attitude performance; however, 95th-percentile performance is still beyond narrow-angle camera requirements, and so these performance improvements have a limited effect and do not significantly increase the probability of success of the mission. As a last comment, it could also be argued that

Table 7
Overall attitude performance with misaligned solar arrays.

Solar array misalignment	Percentile	$\varepsilon_{mean}(\text{deg})$	$\varepsilon_{max}(\text{deg})$	Time within FOV (%)	$\omega_{mean}(\text{deg/s})$	$\omega_{max}(\text{deg/s})$
1 deg	50th	0.008	0.008	100.0	0.005	0.008
	75th	0.017	0.021	99.47	0.022	0.039
	90th	0.149	0.198	94.70	0.217	0.388
	95th	3.282	4.020	0.000	3.289	4.415
5 deg	50th	0.008	0.009	100.0	0.006	0.010
	75th	0.018	0.023	99.47	0.042	0.078
	90th	0.223	0.278	92.18	0.851	1.485
	95th	6.991	8.735	0.000	10.65	12.45

Table 8
Overall attitude performance with upgraded reaction wheel.

Reaction wheel upgrade	Percentile	$\varepsilon_{mean}(\text{deg})$	$\varepsilon_{max}(\text{deg})$	Time within FOV (%)	$\omega_{mean}(\text{deg/s})$	$\omega_{max}(\text{deg/s})$
$T_{w,lim} = 70 \text{ mN} \cdot \text{m}$	50th	0.008	0.008	100.0	0.004	0.007
	75th	0.017	0.021	99.48	0.017	0.031
	90th	0.129	0.166	95.40	0.145	0.265
	95th	2.197	2.581	22.72	1.672	2.291
$T_{w,lim} = 70 \text{ mN} \cdot \text{m}$ $H_{w,lim} = 1 \text{ N} \cdot \text{m} \cdot \text{s}$	50th	0.008	0.008	100.0	0.004	0.007
	75th	0.017	0.021	99.47	0.017	0.031
	90th	0.140	0.168	95.25	0.151	0.261
	95th	2.006	2.852	27.30	1.659	2.657

increasing only the torque capability has comparable improvements to allocating a larger reaction wheel, and so a torque capability improvement may be more recommendable in a mass-performance trade-off analysis.

7. Conclusions

This paper provides a detailed assessment of the expected attitude performance of JAXA's SC B1 in the 2029 Comet-I mission (ESA-JAXA collaboration). Comet-I will face exceptional challenges as it attempts the first fly-by of a long-period comet, with a highly-active and uncertain dust environment, and large and also uncertain relative fly-by speeds. Evaluation of attitude performance through such an uncertain and extreme environment becomes thus essential to assess the probability of success of the mission and of its science phase. In support of the design and development of JAXA's 30-kg, 24U-sized spacecraft, this study characterizes the effect of dust particle impacts on the attitude of the spacecraft, evaluates the likelihood of fulfilling science camera requirements, analyzes the effect of main environment and mission factors, proposes a strategy for selection of control gains, and discusses potential solutions to improve attitude performance.

Initial analysis leads to the conclusion that particles of mass 10^{-8} – 10^{-5} kg represent the most relevant source of attitude perturbation, since larger particles (10^{-5} – 10^{-1} kg), which are more unlikely to be encountered, commonly result in the loss of attitude control or may critically damage the spacecraft; and smaller particles (10^{-11} – 10^{-8} kg), which are more numerous, result in perturbations orders of magnitude smaller than attitude requirements that can be understood as high-frequency jitter (relevant to image acquisition). In terms of fly-by altitude, which is also highly uncertain, it is seen that there is a probability larger than 90% of fulfilling attitude requirements for missions with closest approach above 600 km, and this probability is maintained above 75% unless the fly-by altitude is below 300 km. Saturation of reaction wheels is also shown to not be reached, regardless of fly-by altitude, given the short duration of fly-by trajectories (between 20 min and 2 h).

When fly-by altitude is incorporated as a stochastic variable in the analysis, it is in fact concluded that the overall probability of fulfilling science camera requirements is above 90%. This conclusion holds true also when considering the potential enhancement of momentum transfer due to hypervelocity impacts and ejecta generated through perforation/cratering of spacecraft surfaces. Analysis also shows that proper alignment of solar arrays parallel to the incoming flow of particles is essential to attitude performance, since misalignments even below 5 degrees can induce large angular velocities and decrease probability of success below 90%. Lastly, it is shown that upgrading the reaction wheel that is aligned with the camera line-of-sight (e.g., larger torque or angular momentum capability) can reduce pointing errors and angular velocities, but such

performance improvements do not make a significant impact on the probability of success.

Recommendations for JAXA's SC B1 finally include a strategy for selection of attitude control gains, which takes into consideration the uncertainties of the encountered dust environment, potential reaction wheel upgrades are shown to not have a significant effect on attitude performance, and, perhaps most importantly, proper alignment of solar arrays is shown to be essential to maintaining probabilities of success above 90%. This paper ultimately provides a detailed attitude performance analysis and assessment of probability of success for a first-of-a-kind mission to a long-period comet, characterized by unprecedented levels of environment uncertainty and extremity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

- Blue Canyon Technologies, 2021. Blue Canyon Technologies' Reaction Wheels. Boulder, CO, USA.
- Boe, B., Jedicke, R., Meech, K.J., Wiegert, P., Weryk, R.J., Chambers, K. C., Denneau, L., Kaiser, N., Kudritzki, R.-P., Magnier, E.A., Wainscoat, R.J., Waters, C., 2019. The Orbit and Size-frequency Distribution of Long Period Comets Observed by Pan-STARRS1. *Icarus* 333, 252–272. <https://doi.org/10.1016/j.icarus.2019.05.034>.
- Comet-I Dust Hazard Assessment Team, 2021. Comet Interceptor Dust Hazard Assessment Using the Engineering Dust Coma Model (EDCM) Version 4.0.
- Esa, 2019. CDF Study Report - Comet Interceptor - Assessment of Mission to Intercept a Long Period Comet or Interplanetary Object. Noordwijk, The Netherlands.
- Grün, E., Agarwal, J., Altobelli, N., Altwegg, K., Bentley, M.S., Biver, N., Della Corte, V., Edberg, N., Feldman, P.D., Galand, M., Geiger, B., Götz, C., Grieger, B., Güttler, C., Henri, P., Hofstadter, M., Horanyi, M., Jehin, E., Krüger, H., Lee, S., Mannel, T., Morales, E., Mousis, O., Müller, M., Opitom, C., Rotundi, A., Schmied, R., Schmidt, F., Sierks, H., Snodgrass, C., Soja, R.H., Sommer, M., Srama, R., Tzou, C.Y., Vincent, J.B., Yanamandra-Fisher, P., A'Hearn, M.F., Erikson, A.I., Barbieri, C., Barucci, M.A., Bertaux, J.L., Bertini, I., Burch, J., Colangeli, L., Cremonese, G., Da Deppo, V., Davidsson, B., Debei, S., De Cecco, M., Deller, J., Feaga, L.M., Ferrari, M., Fornasier, S., Fulle, M., Gicquel, A., Gillon, M., Green, S.F., Groussin, O., Gutiérrez, P.J., Hofmann, M., Hviid, S.F., Ip, W.H., Ivanovski, S., Jorda, L., Keller, H.U., Knight, M.M., Knollenberg, J., Koschny, D., Kramm, J.R., Kührt, E., Küppers, M., Lamy, P.L., Lara, L.M., Lazzarin, M., López-Moreno, J.J., Manfroid, J., Mazzotta Epifani, E., Marzari, F., Naletto, G., Oklay, N., Palumbo, P., Wm Parker, J., Rickman, H., Rodrigo, R., Rodriguez, J., Schindhelm, E., Shi, X., Sordini, R., Steffl, A.J., Stern, S.A., Thomas, N., Tubiana, C., Weaver, H.A., Weissman, P., Zakharov, V.V., Taylor, M.G.G.T., 2016. The 2016 Feb 19 Outburst of Comet 67P/CG: An ESA Rosetta Multi-instrument Study. *Mon. Not. R. Astron. Soc.* 462, S220–S234. <https://doi.org/10.1093/mnras/stw2088>.
- Haslebach, N., Gerig, S.B., Thomas, N., Marschall, R., Zakharov, V., Tubiana, C., 2022. A Numerical Model of Dust Particle Impacts During a Cometary Encounter with Application to ESA's Comet Interceptor Mission. *Acta Astronaut.* 195, 243–250. <https://doi.org/10.1016/j.actaastro.2022.02.023>.

- Hegel, D., 2016. FlexCore - Low-cost Attitude Determination and Control Enabling High-performance Small Spacecraft. In: Small Satellite Conference. Logan, UT, USA, pp. 1–8.
- Hormann, K., Agathos, A., 2001. The Point in Polygon Problem for Arbitrary Polygons. *Comput. Geom. Theory Appl.* 20, 131–144. [https://doi.org/10.1016/S0925-7721\(01\)00012-8](https://doi.org/10.1016/S0925-7721(01)00012-8).
- IADC WG3, 2013. Characterization of Ejecta From HVI on Spacecraft Outer Surfaces, IADC-11-05.
- Institute of Space Systems, 2020. Enhancement of S/C Fragmentation and Environment Evolution Models. Braunschweig, Germany.
- JAXA Comet Interceptor Team, 2021. Comet Interceptor Probe B1 Design Report Document. Sagami-hara, Japan, New York.
- Krüger, H., Kobayashi, M., Strub, P., Klostermeyer, G.M., Sommer, M., Kimura, H., Grün, E., Srama, R., 2021. Modelling Cometary Meteoroid Stream Traverses of the Martian Moons eXploration (MMX) Spacecraft en route to Phobos. *Earth, Planets Sp.* 73. <https://doi.org/10.1186/s40623-021-01412-5>.
- Kumar, K.D., Godard, A., N., Sinha, M., 2018. Fault-tolerant Attitude Control of Miniature Satellites Using Reaction Wheels. *Acta Astronaut.* 151, 206–216. <https://doi.org/10.1016/j.actaastro.2018.05.004>.
- Lee, A.Y., 2016. Risk Assessment of Cassini Sun Sensor Integrity due to Hypervelocity Impact of Saturn Dust Particles. In: AIAA (Ed.), AIAA Guidance, Navigation, and Control Conference. San Diego, CA, USA. <https://doi.org/10.2514/6.2016-2086>
- Lisse, C.M., Combi, M.R., Farnham, T.L., Russo, N.D., Sandford, S., Cheng, A.F., Fink, U., Harris, W.M., McMahon, J., Scheeres, D.J., Weaver, H.A., Leary, J., 2022. Operating Spacecraft Around Comets: Evaluation of the Near-nucleus Environment. *Acta Astronaut.* 195, 365–378. <https://doi.org/10.1016/j.actaastro.2021.11.030>.
- Marshall, R., Zakharov, V., Tubiana, C., Kelley, M.S.P., Della Corte, V., 2021. Dust Hazard Assessment using the Engineering Dust Coma Model of the Comet Interceptor Mission, in: European Planetary Science Congress. EPSC2021-540, Online. <https://doi.org/10.5194/epsc2021-540>.
- McDonnell, J.A.M., 2002. Momentum Enhancement in Hypervelocity Impacts: Parameters for Space Debris and Meteoroid Perturbations, in: In: Proceedings of the Fifth Cranfield Conference on Dynamics and Control of Systems and Structures in Space, pp. 1–10.
- McDonnell, J.A.M., Alexander, W.M., Burton, W.M., Bussolotti, E., Clark, D.H., Grard, R.J.L., Grün, E., Hanner, M.S., Hughes, D.W., Igenbergs, E., Kuczer, H., Lindblad, B.A., Mandeville, J.-C., Minafra, A., Schwehm, G.H., Sekanina, Z., Wallis, M.K., Zarnecki, J.C., Chakaveh, S.C., Evans, G.C., Evans, S.T., Firth, J.G., Littler, A. N., Massonne, L., Olearczyk, R.E., Pankiewicz, G.S., Stevenson, T.J., Turner, R.F., 1986. Dust Density and Mass Distribution Near Comet Halley from Giotto Observations. *Nature* 321, 338–341. <https://doi.org/10.1038/321338a0>.
- Merouane, S., Zaprudin, B., Stenzel, O., Langevin, Y., Altobelli, N., Della Corte, V., Fischer, H., Fulle, M., Hornung, K., Silén, J., Ligier, N., Rotundi, A., Ryno, J., Schulz, R., Hilchenbach, M., Kissel, J., 2016. Dust Particle Flux and Size Distribution in the Coma of 67P/Churyumov-Gerasimenko Measured in-situ by the COSIMA Instrument On-board Rosetta. *Astron. Astrophys.* 596, 1–12. <https://doi.org/10.1051/0004-6361/201527958>.
- Design, M.M.A., 2021. eHaWK 27AS112. Louisville, CO, USA.
- Moretto, M., McMahon, J., 2020. Evolution of Orbits about Comets with Arbitrary Comae. *Celest. Mech. Dyn. Astron.* 132, 1–28. <https://doi.org/10.1007/s10569-020-09973-5>.
- Nasa, 2020. State-of-the-Art Small Spacecraft Technology. NASA Technical Report, Moffett Field, CA, USA.
- Nysmith, C.R., Denardo, B.P., 1969. Experimental Investigation of the Momentum Transfer Associated with Impact into Thin Aluminum Targets. Moffett Field, CA, USA.
- Pérez-Ayúcar, M., Ashman, M., Almeida, M., Sitjà, M.C., García Beteta, J.J., Hoofs, R., Kueppers, M., Yaseli, J.M., Merritt, D., Nespoli, F., Suarez, E.S., 2018. The Rosetta Science Operations and Planning Implementation. *Acta Astronaut.* 152, 163–174. <https://doi.org/10.1016/j.actaastro.2018.07.049>.
- Preda, V., Hyslop, A., Bennani, S., 2022. Optimal Science-time Reorientation Policy for the Comet Interceptor Flyby via Sequential Convex Programming. *CEAS Sp. J.* 14, 173–186. <https://doi.org/10.1007/s12567-021-00368-2>.
- Putzar, R., Watson, E., Schimmerohn, M., Kärräng, P., Millinger, M., 2019. How Hypervelocity Impacts Can Affect the LISA Mission - The MIRAD Study. In: Proceedings of the International Astronautical Congress, pp. 1–10.
- Rembor, M., 1993. Momentum Exchange at Particle Impacts - A Calibration Study for the Giotto/DIDSY Momentum Sensors. University of Kent.
- Rival, M., Mandeville, J.C., 1999. Modeling of Ejecta Produced upon Hypervelocity Impacts. *Sp. Debris* 1, 45–57. <https://doi.org/10.1023/A:1010021403591>.
- Sagnières, L.B.M., Sharf, I., 2017. Stochastic Modeling of Hypervelocity Impacts in Attitude Propagation of Space Debris. *Adv. Sp. Res.* 59, 1128–1143. <https://doi.org/10.1016/j.asr.2016.11.030>.
- Sánchez, J.P., Bucci, L., Skuppin, N., 2021. Comet Interceptor: Consolidated Report on Mission Analysis (ESA-COMET-MIS-RP-001).
- Sánchez, J.P., Morante, D., Hermosin, P., Ranuschio, D., Estalella, A., Viera, D., Centuori, S., Jones, G., Snodgrass, C., Levasseur-Regourd, A.C., Tubiana, C., 2021. ESA F-Class Comet Interceptor: Trajectory Design to Intercept a Yet-to-be-discovered Comet. *Acta Astronaut.* 188, 265–277. <https://doi.org/10.1016/j.actaastro.2021.07.014>.
- Snodgrass, C., Jones, G.H., 2019. The European Space Agency's Comet Interceptor lies in wait. *Nat. Commun.* 10, 5418. <https://doi.org/10.1038/s41467-019-13470-1>.
- Vallat, C., Altobelli, N., Geiger, B., Grieger, B., Kueppers, M., Muñoz Crego, C., Moissl, R., Taylor, M.G.G.T., Alexander, C., Buratti, B., Choukroun, M., 2017. The Science Planning Process on the Rosetta Mission. *Acta Astronaut.* 133, 244–257. <https://doi.org/10.1016/j.actaastro.2017.01.018>.
- Wie, B., 2016. Space Vehicle Dynamics and Control, Revised first ed. American Institute of Aeronautics and Astronautics, Inc., Reston, VA, <https://doi.org/10.2514/4.103803>.
- Zakharov, V.V., Rodionov, A.V., Fulle, M., Ivanovski, S.L., Bykov, N. Y., Della Corte, V., Rotundi, A., 2021a. Practical Relations for Assessments of the Gas Coma Parameters. *Icarus* 354. <https://doi.org/10.1016/j.icarus.2020.114091>.
- Zakharov, V.V., Rotundi, A., Della Corte, V., Fulle, M., Ivanovski, S.L., Rodionov, A.V., Bykov, N.Y., 2021b. On the Similarity of Dust Flows in the Inner Coma of Comets. *Icarus* 364. <https://doi.org/10.1016/j.icarus.2021.114476>.



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