

A comparative reliability analysis of ballistic deployments on binary asteroids

Onur Çelik^{a,*}, Joan Pau Sánchez^b, Özgür Karatekin^c, Birgit Ritter^c

^a*Department of Space and Astronautical Science, The Graduate University for Advanced Studies (SOKENDAI), 252-5210, Sagamihara, Japan*

^b*Space Research Group, Centre of Autonomous and Cyber-Physical Systems, Cranfield University, MK43 0AL, Bedford, United Kingdom*

^c*Reference Systems and Planetology, the Royal Observatory of Belgium (ROB), 1180, Brussels, Belgium*

Abstract

Small body missions can significantly benefit from deploying small landing systems onto the surface of the visited object. Despite the potential benefit that they may bring, deployments of landers in small body environments may entail significant mission design challenges. This paper thus addresses the potential of ballistic landing opportunities in binary asteroid moons from a mission design perspective, particularly focusing on reliability aspects of the trajectories. Two binaries that were previously identified as target bodies in several missions/proposals, Didymos and 1996 FG3, are considered in this paper. The dynamics near them are modelled by means of the Circular Restricted Three Body Problem, which provides a reasonable representation of a standard binary system. Natural landing trajectories that allow both minimum-velocity local-vertical touchdown and deployment from a safe dis-

*Corresponding author

Email addresses: onur.celik@ac.jaxa.jp (Onur Çelik),
jp.sanchez@cranfield.ac.uk (Joan Pau Sánchez), ozgur.karatekin@observatory.be
(Özgür Karatekin), birgit.ritter@observatory.be (Birgit Ritter)

Preprint submitted to Acta Astronautica

January 17, 2018

tance are investigated. Coefficient of restitution values are used as a design parameter to compute the first touchdown speeds that ensure sufficient reliability of landing trajectories. A simple reliability index, which is derived via uncertainty ellipsoid from covariance analysis, is introduced to create a global reliability map across the asteroid surfaces. Assuming 3σ deployment errors on the order of 90 m and 2 cm/s, the results show that ballistic landing operations are likely to be successful for larger binary moons if the deployments target near equatorial regions within longitude range 320° – 20° . It has also been shown that the deployments to smaller binary moons may require higher accuracy in navigation and deployment systems in their mothership, and/or closer deployment distances.

Keywords: Binary asteroids, Landing, Astrodynamics, Trajectory design, Covariance analysis

1. Introduction

Near-Earth asteroids (NEAs) are the easiest celestial objects to be reached from Earth (excl. the Moon) and offer a unique window to the early stages of accretion and differentiation of the inner planets of the solar system. Among NEAs, asteroids with moons constitute a considerable portion, of about 16% according to recent estimates [1]. However, no mission has aimed for a binary system, since the visit to the Ida-Dactyl system by Galileo spacecraft. On the other hand, among the variety of missions proposed to asteroids, or to small bodies in general, the interest in binary asteroids also seems to grow. The planetary science community has a profound interest in returning to a binary, particularly with rendezvous missions. Such missions have a strong motiva-

tion to settle the debate on the formation of these primitive, information-rich planetary bodies. However, apart from scientific curiosity, and its potential commercial value, missions to binary asteroids are also important as test beds for possible asteroid deflection missions in the future. The threat of asteroid impacts on Earth has been taken seriously and a variety of techniques have been proposed to deflect potentially hazardous asteroids [2]. One of these is the kinetic impactor technique, which involves a high-speed spacecraft which is to intercept a target asteroid in order to change its orbital course to mitigate the risk of a potential impact [3]. Binary asteroids are ideal testbeds to demonstrate the capabilities of kinetic impactors, as change in orbital period of the natural moon of the asteroid, thereafter called the secondary, after an impact would likely be observed by ground-based observation systems. Along with this line of motivations on science and technology demonstration, several Europe- and US-led, or collaborative missions have been proposed within the last decade, such as Marco Polo-R, Binary Asteroid in-situ Exploration (BASiX), and Asteroid Impact and Deflection Assessment (AIDA) [4, 5, 6].

As being the most recent example, the goal of the joint NASA/ESA multi-spacecraft mission proposal AIDA is to test the kinetic impactor technique in the binary asteroid (65803) 1996GT Didymos [6]. Between the proposed two spacecraft, NASA spacecraft Double Asteroid Redirection Test (DART) is planned to perform a high-speed impact on the smaller companion of Didymos (informally called Didymoon). Whereas the ESA spacecraft Asteroid Impact Mission (AIM) has science tasks to provide an observational support to theoretical asteroid deflection studies, which ultimately need the mechanical and structural properties, porosity, cohesion of the target, as well as to

37 collect the necessary data to constrain the formation of this particular binary
 38 system, and possibly provide an evidence for the formation of other binaries,
 39 as well. The original AIM proposal also included MASCOT-2 lander de-
 40 signed by German Aerospace Center (DLR) to perform in-situ observations,
 41 and two CubeSats to be deployed near the binary system [7]. As a response
 42 to the CubeSat call, the Royal Observatory of Belgium (ROB) proposed two
 43 3U CubeSats to land on Didymoon, named as Asteroid Geophysical Explorer
 44 (AGEX) mission [8]. Even if AIM's future appears to be uncertain since 2016
 45 ESA ministerial, the above examples indicate an interest to land small science
 46 packages onto the surface of binary systems.

47 Landing on an asteroid or a comet substantially differs from landing on a
 48 deeper gravity well, such as Mars and the Moon. The extremely weak grav-
 49 itational environment found in small bodies makes purely ballistic descent
 50 trajectories a viable option, since the touchdown velocities can be safely man-
 51 aged only by simple structural modifications on the craft. It could also be
 52 a preferable solution for motherships, such as AIM, to deploy landers from
 53 a safer distance, since the dynamical environment around asteroids imposes
 54 non-negligible risks to low-altitude landing operations. This makes ballistic
 55 landing trajectories ideal conduits for lander craft that possess only minimal
 56 or no control capabilities. However, the very same gravitational environment
 57 entails a completely different challenge: Unless sufficient energy is damped
 58 at touchdown, the lander may well bounce and subsequently escape from
 59 the asteroid, or bounce into a badly illuminated conditions, which would se-
 60 riously jeopardize the mission [9]. Therefore, research on delivering small,
 61 unpowered landers on binary surface has gained a considerable interest.

62 In binary asteroid systems, one can find natural trajectories to deliver sci-
 63 ence packages by exploiting the three-body problem. Such strategy was first
 64 studied by Tardivel and Scheeres [10], in which they considered the vicinity
 65 of equilibrium points of binary systems in Circular Restricted Three-Body
 66 Problem (CR3BP) as deployment locations, and defined the first intersec-
 67 tion of a trajectory with the surface as landing [10]. This work was followed
 68 by a study on the deployment strategy of a small lander in binary asteroid
 69 1996 FG3, back-up target of Marco Polo-R mission proposal [11]. More-
 70 over, within the context of MASCOT-2 lander, Tardivel et al. discussed
 71 passive landing opportunities on Didymoon [12]. Tardivel later published
 72 an additional study on optimization of ballistic landings in binary asteroid
 73 [13]. Along the same line of studies, Ferrari and Lavagna performed a tra-
 74 jectory design study and Monte Carlo simulations against uncertainties for
 75 MASCOT-2 [14]. In a more recent study, Çelik and Sánchez proposed a
 76 new technique in CR3BP to search opportunities for ballistic soft landing in
 77 binary asteroids [15]. This technique defines a landing in local vertical and
 78 utilizes a bisection search algorithm to find minimum energy trajectories in
 79 backwards propagation from the surface.

80 This paper focuses on design aspects of ballistic landings of small lan-
 81 ders onto the surfaces natural moons of binary asteroids. Çelik and Sánchez
 82 (2017) previously showed that landing trajectories onto larger companions of
 83 binaries (thereafter called as the primaries) entail higher energy landing tra-
 84 jectories, which; on the one hand may put the payload on the lander at risk
 85 due to the higher touchdown velocities, and on the other hand, do not guar-
 86 antee that the lander will remain in the surface of the primary, unless very

low coefficient of restitution can be ensured [15]. Hence, this paper focuses only on landing in the secondary, which was previously shown to potentially enable ballistic soft landing [15]. The paper particularly addresses the reliability aspects of the deployment operations under realistic uncertainties and errors in navigation and deployment systems. Two binaries are selected as targets: Didymos and 1996 FG3. A spherical shape and point mass gravity are assumed for both companions. A dense grid of first touchdown points is created and distributed homogeneously on the surface, whose locations are described by their latitudes and longitudes. Trajectories are then generated from each point in by applying the methodology developed in [15]. This allows us to obtain nominal trajectories under ideal conditions, as well as to generate a database of reachable regions and characteristics of landings on the surface as a function of landing location. One of the useful information in the database is touchdown speeds, which is the only parameter that characterizes the landing trajectory for a given landing site, due to the definition of the local vertical landing. Thus, they can be used to compute the worst case estimation of the required energy damping, or coefficient of restitution, in order to stay near the binary system after the first touchdown. In this paper, first, the reliability of landing trajectories to reachable locations with the worst case coefficient of restitution are investigated in a simple deployment model with the covariance analysis. The covariance matrices for a global set of landing conditions are propagated to the surface from the deployment points, and the regions with more robust landing conditions are identified.

The reliability of the nominal trajectories are next discussed by generating landing conditions for a specific coefficient of restitution, navigation and

112 deployment errors. A reliability index is introduced from the cross-sectional
 113 area of uncertainty ellipsoid (computed after the covariance propagation)
 114 in the local topocentric frame of landing site and the cross-sectional area of
 115 subject asteroid, in order to assess the robustness of the deployment operation
 116 at different landing sites. The covariance analysis and the reliability index are
 117 tested by Monte Carlo analyses for further assessment of the methodology.
 118 By creating a multifaceted global reliability map of landings, this paper aims
 119 to draw a preliminary conclusion about how non-idealities might possibly
 120 affect the success of landing operations of an unpowered lander in binary
 121 asteroid surfaces.

122 The remainder of the paper is structured as follows: Section 2 intro-
 123 duces the binary asteroid model; Section 3 introduces the trajectory design
 124 methodology and the deployment model, and discusses the results of land-
 125 ing speeds, coefficients of restitution and deployment opportunities for the
 126 minimum touchdown speed case. Section 4 describes the navigation model
 127 and discusses the results of uncertainty analysis. Finally, Section 5 provides
 128 conclusions and final remarks.

129 **2. Binary Asteroid Model**

130 This paper considers (65803) 1996GT Didymos and (175706) 1996 FG3
 131 as targets for our ballistic landing analysis. These are previously identified
 132 targets (with rather frequent launch opportunities) of at least three mission
 133 proposals, with a small lander option [4, 5, 6]. Moreover, their physical
 134 properties are quite different from each other, as shown in Table 1 below.

135 As mentioned earlier, this paper assumes binary asteroids which are com-

Table 1: Physical properties of (65803) Didymos & 1996FG3. Didymain and 1996 FG₃ A denote the primaries, whereas Didymoon and 1996 FG₃-B denote the secondaries in the binary systems, respectively.

Property	Didymain	Didymoon	1996 FG3-A	1996 FG3-B
Diameter [km]	0.775	0.163	1.690	0.490
Density [kg/m ³]	2146		1300	
Mass [kg]	5.23 x 10 ¹¹	4.89 x 10 ⁹	3.29 x 10 ¹²	8.01 x 10 ¹⁰
Mass parameter ($\frac{m_2}{m_1+m_2}$) [-]	0.0092		0.0238	
Mutual orbit radius [km]	1.18		3.00	
Mutual orbit period [h]	11.9		16.15	

posed of two spherical bodies with the same constant density. The binary nature of the asteroids allows us to use the CR3BP as the dynamical framework to the motion of a lander, whose details are going to be discussed in the next section. The CR3BP is generally derived in the normalized distance, time and mass units, of which the normalized mass (mass parameter) is provided for both asteroids in Table 1. Mass parameter is one of two main parameters that uniquely defines the dynamical environment near the binary asteroid, together with the ratio between the mutual orbit semi-major axis and the primary diameter (the a -to- D_{pri} ratio). The spherical asteroid and the same density assumptions conveniently allow us to redefine mass parameter in terms of the secondary-to-primary diameter ratio (the D_{sec} -to- D_{pri} ratio). Please, refer to [15] for more comprehensive description and justification of the method. In Çelik and Sánchez [15], the statistics of these two properties among the NEA binaries with known (not assumed) densities were investigated, and it was found that the D_{sec} -to- D_{pri} ratio has a mean of 0.28,

151 while the a -to- D_{pri} ratio has a mean of 2.20 [15]. Those two ratio properties
 152 are 0.21 and 1.52 for Didymos, and 0.29 and 1.78 for 1996FG3, respectively,
 153 and this locates them near the *average* ratio properties of the NEA binaries.
 154 This suggests that the analyses that will be presented in the next sections not
 155 only cover a wider range of binaries in size, but also a good representation of
 156 the currently known binary population in terms of the ratio properties. This
 157 result has also been illustrated in Figure 1, which presents the distribution
 158 of the ratio properties of the NEA binaries with known densities. It can be
 159 noted from the figure that Didymos and 1996FG3 fall near the middle of the
 160 data points.

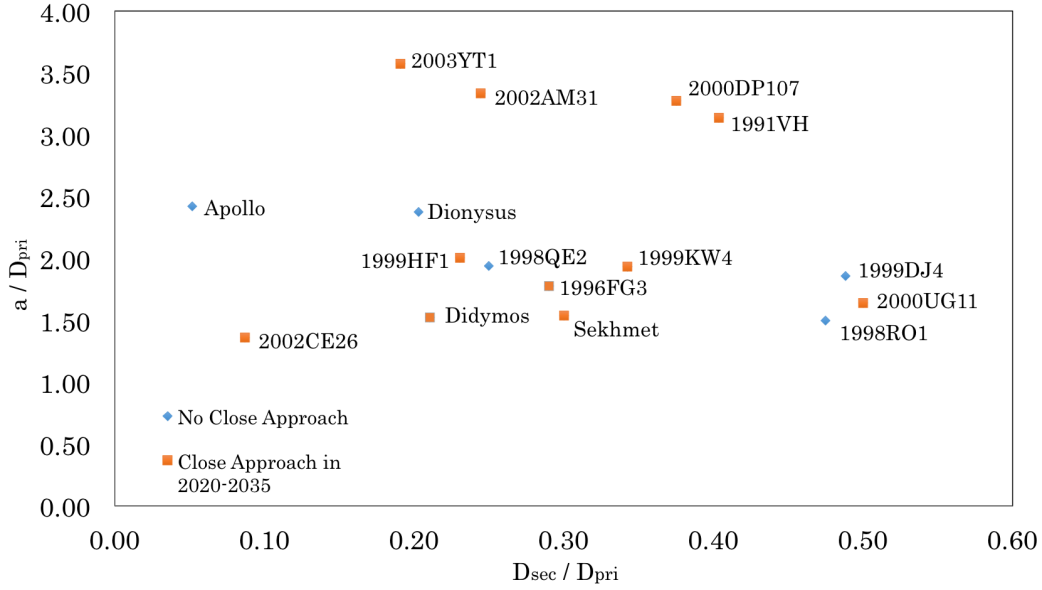


Figure 1: Close approaches of the NEA binaries (<0.2 AU) in 2020-2035 time frame. (a : semi-major axis of secondary orbit around primary; D_{pri} is diameter of a spherical primary and D_{sec} is diameter of a spherical secondary.

161 NEA binaries with known densities are represented by a square point in

162 the figure if the referred binary is due to undergo a close encounter with
 163 the Earth during an hypothetical launch window between 2020-2035. Here,
 164 close approach refers to a minimum distance with the Earth of less than 0.2
 165 AU, within which a mission would be justifiable with low energy trajectories
 166 [16]. Among the whole set of NEA binaries, 2000 DP107, 1991 VH and 2000
 167 UG11 are also interesting objects, since a patched conic trajectory analysis
 168 identifies these objects also as accessible during their close approach¹. These
 169 binaries would also be of interest, since as shown in Fig. 1, their semi-major
 170 axis and size ratios are far from the observed average values. Nevertheless,
 171 for the sake of simplicity, only two binary asteroids Didymos and 1996FG3
 172 are going to be analyzed in next sections.

173 **3. Landing Trajectory Design**

174 Let us consider a mothership, in its operational orbit, at a safe distance
 175 from the binary system’s barycentre. A passive lander (or a “science pack-
 176 age”) can be sent onto the surface of one or both of binary companions from
 177 this mothership by exploiting the natural dynamics around the binary sys-
 178 tem. As mentioned earlier, landing trajectories in this dynamical scheme
 179 can be designed in the framework of Circular Restricted Three-Body Prob-
 180 lem (CR3BP), in which third body (i.e. lander) is assumed to move under the
 181 gravitational attraction of primary and secondary (i.e. binary companions)
 182 without effecting their motion about their common centre of mass. The dy-
 183 namical model is traditionally derived in the rotational frame, whose center

¹Patched conic accessibility analysis considered Earth departure v_∞ less than 6 km/s
 and launch performances as expected for Ariane 6.2.

184 is at the barycenter of larger bodies, with x-axis on the line connecting the
185 primary and the secondary, z-axis defined in the direction of the mutual orbit
186 normal and y-axis completing triad [17]. Hence, unless otherwise stated, the
187 models and the results will be provided in this rotating barycentric reference
188 frame.

189 The CR3BP exhibits five equilibria, called the Lagrange points (L1-L5),
190 and five different regimes of motion, expressed in zero-velocity surfaces (ZVS)
191 [17]. For our notional mothership, an operational orbit can be defined in the
192 exterior realm of ZVS, in which the L2 point is closed so that no natural
193 motion is allowed to the interior realm. In this setting, the L2 point presents
194 the lowest energy gate to reach the interior region. Thus, a simple spring
195 mechanism available on a mothership can provide a gentle push to increase
196 the lander's energy in order to open up ZVS at the L2 point and allow motion
197 to the interior realm. The operational orbit of a mothership and deployment
198 strategy are illustrated in Fig. 2.

199 The landing trajectory design in such scenario is tackled in the ground-
200 work study performed by Çelik and Sánchez in the context of a hypothetical
201 binary asteroid, whose properties are a good representation of the known
202 NEA population [15]. In this study, landing is defined in the local vertical of
203 a landing site and described by its latitude and longitude. Such description
204 has the clear advantage of defining a landing by only one parameter, i.e.
205 touchdown speed ($v_{T/D}$), once a specific landing location is defined. The ini-
206 tial state vectors are then propagated backwards from the landing locations
207 on the surface to the exterior realm of ZVS in a specially developed bisection
208 algorithm [15]. The algorithm searches for the minimum energy landings in

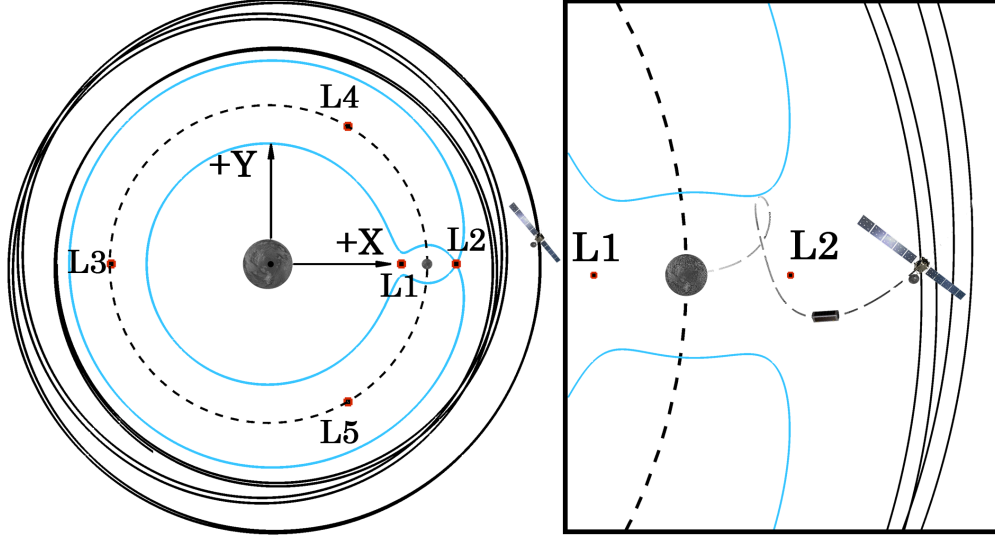


Figure 2: Mission architecture. Operational scenario of the mothership, ZVS closed at L2 (Left). The deployment provides the energy to open ZVS up at L2 (Right).

209 a reverse-engineered, iterative manner from the surface to exterior region of
 210 ZVS. It then allows trajectories to be designed for any arbitrary latitude–
 211 longitude pairs on the surface for any sizes of binary asteroids. Hence, it
 212 generates an overall picture for various features of landing, e.g. energies,
 213 speeds and required maximum coefficient of restitution (ϵ) values. Moreover,
 214 after the resulting trajectories are propagated sufficiently long time, any part
 215 of the trajectory that lies beyond the ZVS with the L2 point energy can be
 216 seen as a potential deployment location. The minimum deployment velocities
 217 at those locations can be estimated by computing the necessary velocity that
 218 closes ZVS at the L2 point, which therefore corresponds to open up ZVS at
 219 the L2 point in forward propagation mode, to allow motion to the interior
 220 realm. For much more detailed explanation on the methodology, the reader

221 is encouraged to refer to the work of Çelik and Sánchez [15].

222 3.1. Landing speed and energy damping

223 The results of landing speeds are provided in Fig. 3. The secondary is
224 assumed to be tidally locked, hence the attitude of secondary can be assumed
225 fixed in the synodic reference frame. 0° represents the prime meridian whose
226 point is arbitrarily defined as to be on the x-axis, directly facing the L2 point.

227 Figure 3 shows that both binaries show similar characteristics in terms
228 of minimum touchdown speeds. Minimum touchdown speeds are observed
229 at the landing sites near the L2 point and in the trailing edge of the far
230 side. Approximately half of the secondary surface is available under 10 cm/s
231 for Didymoon ($\sim 47\%$) and 20 cm/s for 1996 FG3 ($\sim 44\%$). The minimum
232 computed touchdown speeds in Didymoon and 1996 FG3-B are 5.8 cm/s and
233 14.9 cm/s respectively, at the closest point to the L2 point. It is noteworthy
234 that these values are below the two-body escape speed of both Didymos (32.4
235 cm/s) and 1996 FG3 (57.6 cm/s). These escape speeds were computed at
236 the landing point closest to the L2 point as the sum of escape speeds of both
237 bodies. However, as shown by the results in Figure 3, the classical escape
238 velocity is a misleading result, since in order to open up the ZVS at the L2
239 point, one requires energies that can be achieved with speeds smaller than
240 5 cm/s. Therefore, a lander can in fact escape with speeds lower than the
241 two-body escape velocity if a proper geometry of the escape motion is found.

242 As discussed earlier, the trajectory design methodology also enables us
243 to estimate the minimum coefficient of restitution ϵ on the surface. ϵ in
244 this study refers to the simple interaction between surface and the landing
245 spacecraft with a specific value, similar to a bouncing ball on a surface and

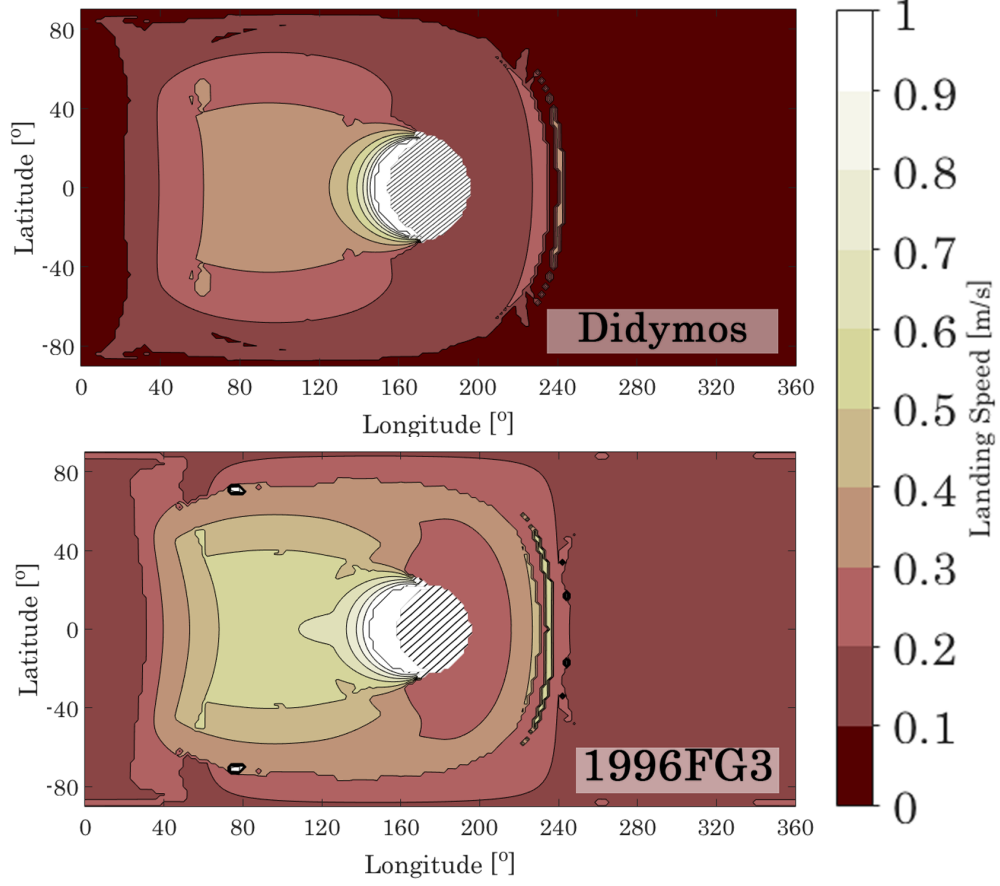


Figure 3: Minimum touchdown speeds on Didymos and 1996FG3-B surface. The diagonal texture in the middle of figures shows unavailability of ballistic landing to those regions with the trajectory design algorithm discussed in the text. The estimated two-body escape speeds are 32.4 cm/s and 57.6 cm/s for Didymos and 1996FG3, respectively.

246 can be described in both local vertical and local horizontal. However, this
 247 paper only concerns with ϵ values in local vertical, and assumes that the
 248 outgoing velocity is in the same plane as the incoming velocity and the surface
 249 normal vector. This may change due to surface features, such as boulders or

250 rocks, however that is not considered here. ϵ value then defines the energy
 251 dissipation due to surface properties, as in Eq. 1 in its simplest way.

$$\begin{aligned}
 \mathbf{v}_{LV}^- &= (\hat{\mathbf{n}} \cdot \mathbf{v}) \cdot \mathbf{v} \\
 \mathbf{v}_{LV}^+ &= -\epsilon (\hat{\mathbf{n}} \cdot \mathbf{v}) \cdot \mathbf{v} \\
 \implies \mathbf{v}_{LV}^+ &= -\epsilon \mathbf{v}_{LV}^-
 \end{aligned} \tag{1}$$

252 where $\mathbf{v}_{LV}$ is the local vertical velocity, $\hat{\mathbf{n}}$ is local normal unit vector and su-
 253 perscripts $(-)$ and $(+)$ denote incoming and outgoing velocities, respectively.
 254 ϵ values must typically be between 0 and 1, but it may be considerably
 255 different in local horizontal and vertical directions [18, 19].

256 We can now compute ϵ values to close ZVS at the L1 point for landings
 257 depicted in Fig 3. Basically, this is a rough estimate of how much energy
 258 needs to be dissipated at touchdown, so that motion of a lander would be
 259 trapped near the secondary of binary system. In the rest of the paper, ϵ will
 260 always refer to the required coefficient of restitution to reduce the energy
 261 below that of the L1 point. The results are presented in Fig. 4.

262 In a clear agreement with the results in Fig. 3, the regions of lowest touch-
 263 down speeds show higher ϵ values, hinting that very little energy dissipation
 264 would be enough to keep a lander near the binary systems. In the regions of
 265 higher touchdown speeds, on the other hand, the ϵ values begin to decrease
 266 to levels, for which a lander would likely require an active landing system.
 267 Thus, for a purely passive landing, the regions with low landing speed and
 268 high ϵ appear to be more attractive options to consider for deployment.

269 Figure 4 reveals important insights at first glance into the feasibility of the

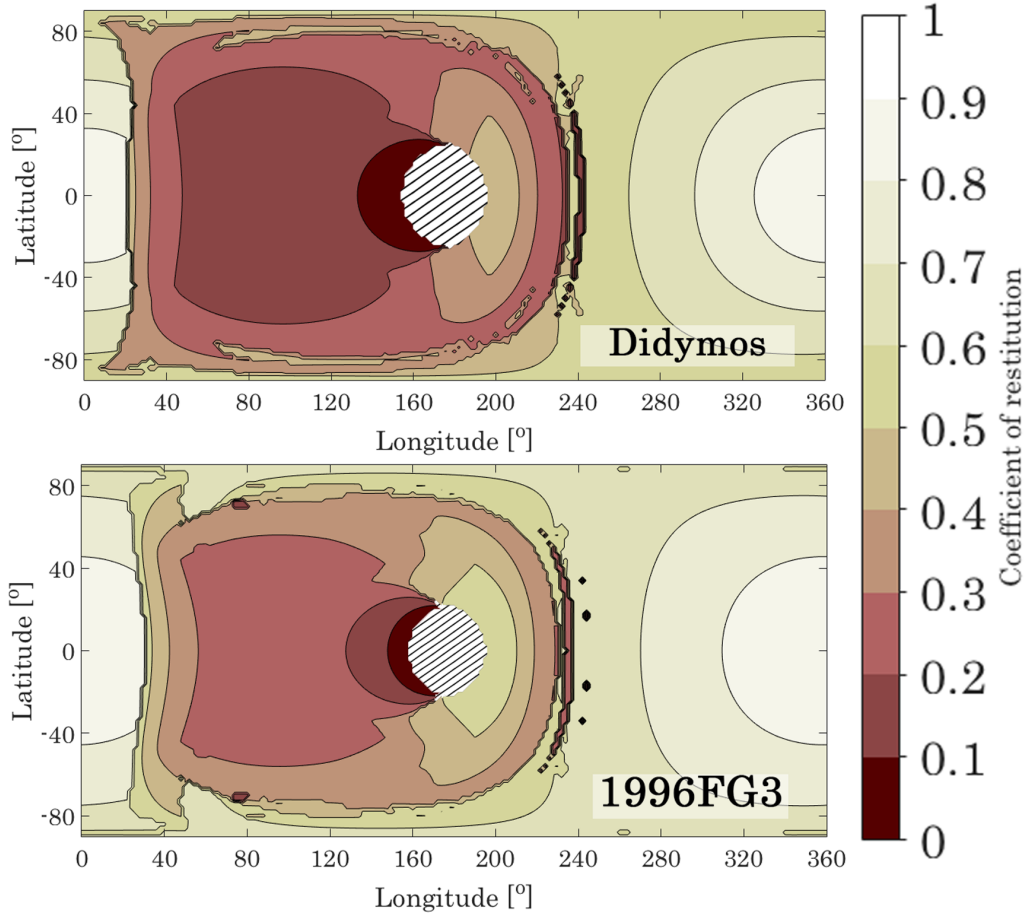


Figure 4: Required coefficient of restitution (ϵ) to close ZVS at the L1 point for both secondaries.

270 ballistic landing in binary asteroid systems. It should be noted at this point
 271 that the coefficient of restitution value in the sampling horn of Hayabusa
 272 at the touchdown was measured as ~ 0.85 [20]. While this value has large
 273 uncertainties, Philae's touchdown on comet 67P/Churyumov-Gerasimenko
 274 revealed that the comet surface is "strongly damping" with ϵ values varying
 275 between ~ 0.2 - 0.5 [21]. Taking this information into account, it is clear that

276 assuming a conservative estimate of ~ 0.9 for ϵ would allow only some reduced
 277 regions in the far side of the secondary. However, more recent theoretical and
 278 experimental studies suggest that appropriate structural design solutions may
 279 well allow $\epsilon \sim 0.6$, or even lower, in the asteroid surfaces [22, 23].

280 The maximum expected ϵ value on the current mission scenarios is there-
 281 fore ~ 0.6 . The results on Fig.4 allow enough room to be more conservative to
 282 provide a margin to this value, therefore $\epsilon = 0.7$ was chosen as the minimum
 283 feasibility criteria of landing operations. Regions that exhibit lower than
 284 this ϵ value are going to be discarded as infeasible. Nevertheless, as shown
 285 in Çelik and Sánchez [15], the results in Fig. 4 are likely to be the worst case
 286 estimates of the actual ϵ values, since the motion after a bounce may allow
 287 further contact with the surface, i.e. more opportunities for energy damping,
 288 before the lander rests on the surface. For more information, the reader may
 289 refer to the other available works in the literature [18, 24, 25, 19, 21].

290 3.2. Deployment model

291 In the deployment operation, the mothership is likely to release the lander
 292 while on a trajectory taking it near to a binary, but still safe according to
 293 the ZVS discussion in Section 3. Thus, we assume that a release trajectory
 294 has a periapsis at the deployment point, and an apoapsis near the sphere
 295 of influence (SOI) of binary system. Then, at the deployment point the
 296 mothership shall have a normalized velocity $\mathbf{v}_{S/C}$, computed through elliptic
 297 Keplerian orbits as:

$$\mathbf{v}_{S/C} = \left(\sqrt{\frac{2}{r_{release}} - \frac{2}{r_{release} + r_{SOI}}} - r_{release} \right) \hat{\boldsymbol{\theta}} \quad (2)$$

where $\hat{\boldsymbol{\theta}} = \hat{\mathbf{h}} \times \hat{\mathbf{r}}$, $\hat{\mathbf{r}}$ is the release position unit radius vector and $\hat{\mathbf{h}}$ is the direction of the ballistic descent trajectory momentum vector. The initial state vector of the ballistic descent $[\mathbf{r}_{release} \ \mathbf{v}_{release}]$ was computed with the aforementioned bisection algorithm [15]. The state vector $[\mathbf{r}_{release} \ \mathbf{v}_{release}]$ is chosen such that two constraints are satisfied:

- Duration of the descent trajectory must be less than 12 h.
- Mothership distance to the barycenter of the binary must be greater than 1.25 times the distance of the L2 point to the barycentre, r_{L2} .

The duration of the descent is set to ensure relatively shorter operation times, while also allowing plenty of opportunities for deployment. And the minimum deployment altitude is scaled with the L2 point distance so that the mothership will always be in a safe distance from the secondary. This distance can be increased or decreased during the design phase in a trade-off between the risk on the mothership and the robustness of the deployment operations. However, note that the deployment distance must always be greater than or equal to the L2 point distance to barycentre due to the particular characteristic of the ballistic landing discussed here. Here, it was chosen arbitrarily with the purpose to define a safer deployment scenario than those studied in previous work by the authors [26], since the further from the secondary surface the more dynamically stable. The deployment altitude in this case corresponds to ~ 440 m for Didymos, ~ 1285 m for 1996 FG3 from the secondary surface when measured on the x-axis of the rotating reference frame.

321 The above deployment model and the constraints are an attempt to gen-
 322 eralize the deployment model for any binary system of interest. Depending
 323 on the dynamical characteristics of a target, multitudes of orbits can be ex-
 324 ploited to fulfill operational and scientific requirements. Examples of those
 325 include direct and retrograde interior orbits around primaries, quasi-satellite
 326 orbits around the secondary, and direct and retrograde exterior and termi-
 327 nator orbits around the binary system, or even orbits around equilateral
 328 Lagrange points of the binary systems [27, 28]. Some of the example orbits
 329 may enable better deployment conditions for certain regions (e.g. poles), but
 330 this is out of scope of the paper.

331 The deployment spring mechanism in the mothership must then provide
 332 an impulse to the lander such that:

$$\mathbf{v}_{spring} = \mathbf{v}_{release} - \mathbf{v}_{S/C} \quad (3)$$

333 Note that, ignoring navigation errors, the release location $\mathbf{r}_{release}$ is as-
 334 sumed to coincide with the position of the mothership, $\mathbf{r}_{S/C}$, at the release
 335 time. According to the above deployment model, a relatively reduced region
 336 of the secondary is available for landing at coefficient of restitution $\epsilon > 0.7$,
 337 and those regions are depicted in Fig. 5. Some regions in the far side are no
 338 longer reachable, due to the fact that the ballistic descent trajectory takes
 339 more than 12 hours from the given deployment distance. This however could
 340 be solved by allowing touchdown speeds larger than the minimum touchdown
 341 velocity (in Fig. 3), as will be seen in the next section.

342 Most of the available deployments are possible with deployment speeds on
 343 the order of ~ 5 cm/s or below, and no deployments are observed with speeds

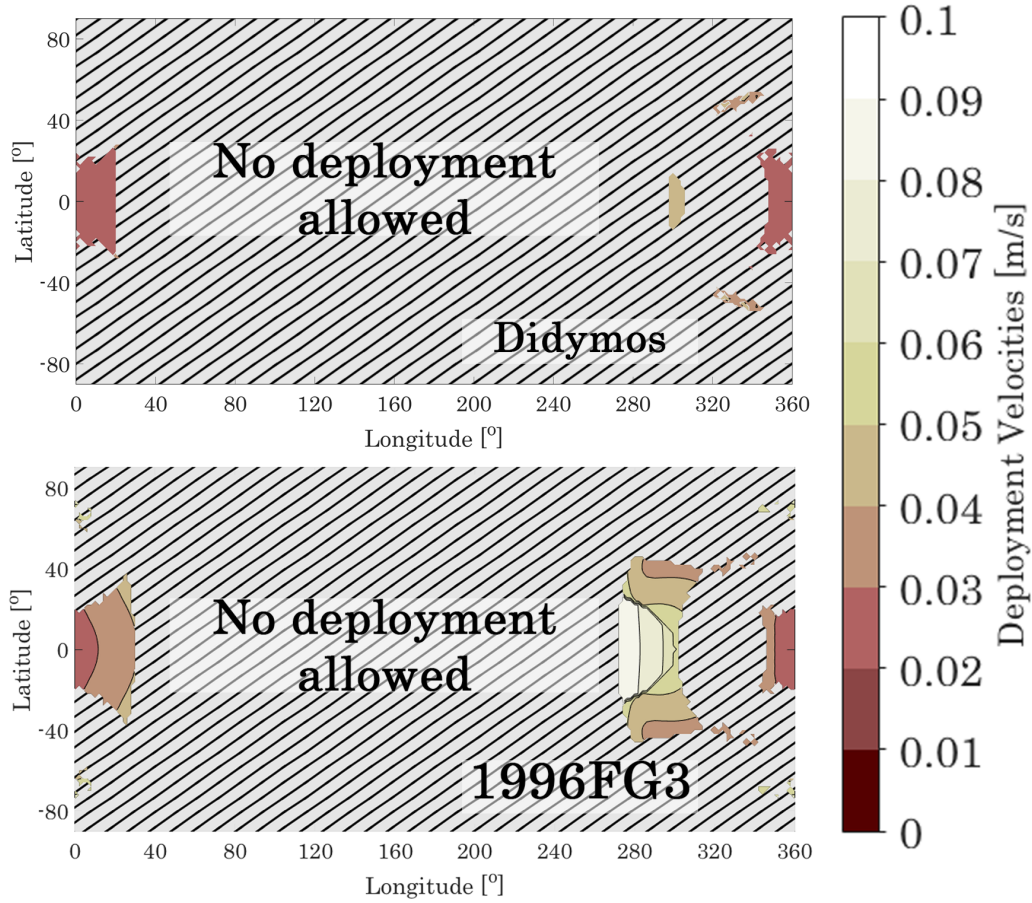


Figure 5: Deployment opportunities with minimum possible touchdown speeds

344 higher than 10 cm/s. While the most deployments to the Didymoon surface
 345 are possible with ~ 2 cm/s, the deployments to the 1996 FG3-B surface are
 346 possible ~ 3 cm/s and above. Note that the Philae's separation speed from
 347 Rosetta was designed to be between 5–50 cm/s with a redundant system
 348 capable of 18 cm/s [19]. AIM's deployment mechanism, on the other hand,
 349 is designed to provide 2–5 cm/s within ± 1 cm/s accuracy [29]. Thus, it seems
 350 that a separation mechanism whose performance in between that of AIM and

351 Rosetta can easily fulfill the deployment demands of both targets.

352 **4. Reliability of ballistic landing trajectories**

353 Ballistic landing trajectories show a compelling prospect to be utilized as
354 a landing strategy, however they also come with their inherent instabilities
355 [30]. Furthermore, trajectories that are generated by the strategy described
356 above are largely idealized with relatively ad-hoc constraints, and it is thus
357 necessary to assess their robustness also against the non-ideal conditions.
358 Particularly, deployments will be affected by the orbit determination errors of
359 the mothership, as well as by the inaccuracies in the deployment mechanism.

360 Many other error sources and perturbations also exist, such as attitude
361 errors or perturbations due to the highly irregular nature of asteroids, par-
362 ticularly in terms of gravity field and shape. This study, however, is only
363 concerned with the GNC and the deployment aspects of non-idealities. The
364 authors' previous works also considered the density (hence gravity) errors in
365 the secondaries [26, 31], however Didymoon and 1996 FG3-B constitute only
366 $\sim 1.2\%$ and $\sim 2.5\%$ of the total mass of their respective systems according to
367 the information in Table 1. It was shown to have a limited effect in the overall
368 robustness of trajectories to reach the surface as compared to the GNC and
369 deployment errors [31, 26], therefore these were not considered in the current
370 study. However, errors in the gravity field of the secondaries may be critical
371 especially in long duration ballistic landing trajectories, and a special care
372 should be taken [32]. Furthermore, solar radiation pressure is found to have
373 a negligible impact due to short time scale of landings. As a final remark,
374 the fact that the spherical shape is assumed may not necessarily be consid-

375 ered as a source of error, because if the shape of the binary was known, the
 376 same strategy could be used to compute new trajectories, as was done for
 377 Philae’s descent trajectory computation [33]. Table 2 summarizes the error
 378 and uncertainty values considered in the paper.

Table 2: Uncertainty and error sources.

Source	3σ
GNC position accuracy	± 90 m
GNC velocity accuracy	± 2 cm/s
Spring magnitude error	3%
Spring angle error	$\pm 4^\circ$

379 The values in the table are realistic and found during the design process
 380 of AIM. It should be noted that the GNC position error in Table 2 is three
 381 times or more than those considered in the previous studies by the authors
 382 [31, 26, 34]. This is due to the GNC system design of AIM, which assumes
 383 no altimeter, but pure relative navigation, with a fusion of image tracking
 384 and the other sensors onboard [35]. The GNC system therefore requires a
 385 comparison of two (or more) consecutive images and measurement of indirect
 386 sources (star tracker and inertial measurement units (IMUs)) to measure the
 387 range to the body, hence inherently increasing the error magnitude.

388 4.1. Deployment covariance analysis

389 A convenient way to analyze impact of the uncertainty and error sources
 390 is covariance analysis. The covariance matrix in this context provides a linear
 391 approximation of the sensitivity of a nominal landing trajectory against the

392 non-idealities. We can translate the information in Table 2 into a diagonal
 393 covariance matrix at release time (t_R) Q_R as:

$$Q_R = \left[\begin{array}{ccc|ccc} \sigma_x^2 & 0 & 0 & 0 & 0 & 0 \\ 0 & \sigma_y^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & \sigma_y^2 & 0 & 0 & 0 \\ \hline 0 & 0 & 0 & \sigma_{v_x}^2 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sigma_{v_y}^2 & 0 \\ 0 & 0 & 0 & 0 & 0 & \sigma_{v_z}^2 \end{array} \right] \quad (4)$$

394 where the diagonal values contain variance of errors in each component of
 395 the state vector. At the instant of deployment, lander and mothership are
 396 assumed to be at the same position, hence the GNC errors applies to the the
 397 lander initial state.

398 The spring angle and magnitude errors, as well as the GNC errors in ve-
 399 locity, will affect the velocity components of the Cartesian covariance matrix
 400 in Eq. 4. For the spring errors, a Monte Carlo sampling with 10000 random
 401 values was used to estimate the variance of the velocity components due to
 402 the spring errors. These variances are then sum to those of the GNC.

403 Q_R can then be propagated to the asteroid surface via state transition
 404 matrix Φ of the nominal trajectory. At the time of touchdown, $t_{T/D}$, the
 405 covariance matrix can be computed as below:

$$Q_{T/D}(t_{T/D}) = \Phi(t_{T/D}, t_R) Q_R(t_R) \Phi^{-1}(t_{T/D}, t_R) \quad (5)$$

406 where subscripts T/D and R denote touchdown and release respectively. The
 407 position errors at touchdown are represented by the 3×3 submatrix in the
 408 top left corner of the covariance matrix at touchdown time $Q(t_{T/D})$:

$$Q_{T/D} = \left[\begin{array}{ccc|c} Q_{xx}^{T/D} & Q_{xy}^{T/D} & Q_{xz}^{T/D} & \\ Q_{yx}^{T/D} & Q_{yy}^{T/D} & Q_{yz}^{T/D} & Q_{TR} \\ Q_{zx}^{T/D} & Q_{zy}^{T/D} & Q_{zz}^{T/D} & \\ \hline & Q_{BL} & & Q_{BR} \end{array} \right] \quad (6)$$

409 However, the position would best be represented in the topocentric co-
 410 ordinate frame using the principal axes of the secondary of the binary of
 411 interest. Therefore, the resulting matrix $Q_{T/D}$ after propagation is rotated
 412 to the local topocentric frame of the landing site [36]. The 3×3 top left sub-
 413 matrix in Eq. 6 is decomposed into its eigenvalues and eigenvectors. In such
 414 approach, the submatrix in Eq. 6 can be represented in the following form:

$$Q_P(t_{T/D}) = \begin{bmatrix} a^2 & 0 & 0 \\ 0 & b^2 & 0 \\ 0 & 0 & c^2 \end{bmatrix} \quad (7)$$

415 where the subscript P denotes position. Square root of the diagonal non-zero
 416 elements a^2 and b^2 in Eq. 7 are semi-major and semi-minor axes (a , b) of the
 417 footprint of the uncertainty ellipsoid representing the 1σ Gausssian distribu-
 418 tion of the deployment errors as projected onto the landing site. Given the
 419 assumed Gaussian distributions for uncertainties and errors, the probability
 420 to obtain a landing trajectory touching-down outside the 1-sigma distribu-
 421 tion footprint is high (i.e. $\sim 61\%$ in a 2D distribution). The probability to
 422 fall instead outside the 2-sigma footprint ($2a$, $2b$) is of about of 14%, while
 423 outside the 3-sigma footprint ($3a$, $3b$) would only be of about 1% [36]. Since

424 a small lander may well be used in a much more daring operation than a
 425 traditional spacecraft, we will assume for now that a landing opportunity
 426 with a 2σ footprint smaller than the cross-sectional area of the secondary
 427 would be a landing opportunity with an acceptable risk.

Thus, a reliability index can be defined such as:

$$A_{2\sigma} = \frac{\pi(2a \cdot 2b)}{\pi \cdot r_s^2} = \frac{4ab}{r_s^2} \quad (8)$$

428 where $A_{2\sigma}$ represents the area of the 2-sigma distribution footprint in units
 429 of the cross-sectional area of the secondary and r_s is the radius of the spher-
 430 ical secondary. Thus, a 2σ distribution footprint $A_{2\sigma} > 1$ would represent a
 431 footprint larger than the asteroid itself, thus indicating a highly unreliable
 432 deployment. One would thus ideally aim for deployments such that $A_{2\sigma} < 1$.
 433 Note that as long as there are uncertainties in a deployment (which is the
 434 case here), $A_{2\sigma}$ will always be greater than 0, and $A_{2\sigma} \in [0, \infty)$.

435 The expression in Eq. 8 allows defining a single figure of merit to measure
 436 landing reliability, which, as is shown later by a Monte Carlo analysis valida-
 437 tion, provides a simple and fast method to obtain a qualitative understanding
 438 of the reliability of the landing opportunity.

439 In the next two subsections, we will analyze how the $A_{2\sigma}$ -index value
 440 appears in both asteroids for minimum and modified touchdown velocities.

441 *4.2. Landing at minimum and modified touchdown speeds*

442 Figure 4 summarizes the results of the 2σ distribution footprint, $A_{2\sigma}$,
 443 analysis for two binaries in the minimum touchdown speed case. The fact
 444 that only small regions display values $A_{2\sigma} \leq 1$ indicates that at the achieved

445 accuracies in navigation and deployment in Table 2, landing trajectories are
 446 not robust enough to provide wider range of reliable landing locations.

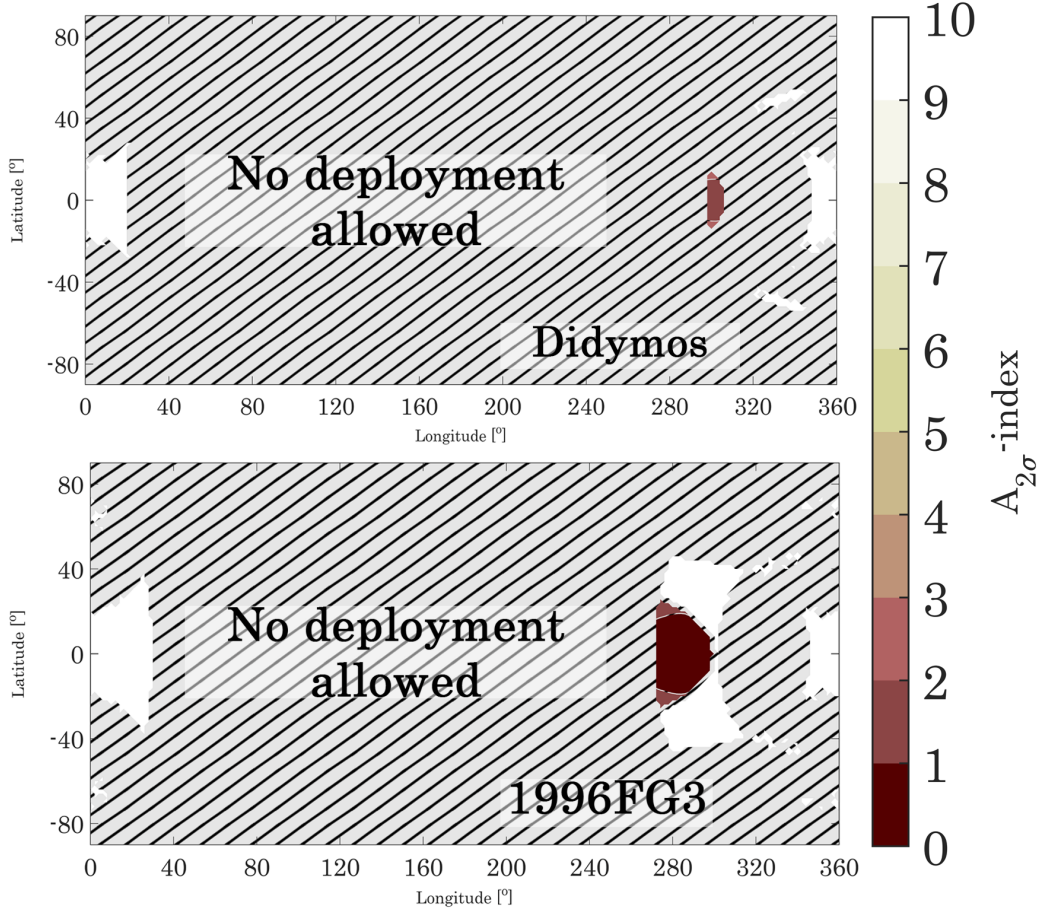


Figure 6: $A_{2\sigma}$ -index for minimum touchdown speeds

447 With the introduced deployment model and the chosen arbitrary safe dis-
 448 tance for deployment, Didymoon surface is almost unreachable at any point
 449 except for very small, scattered islands in the far side. Even among those
 450 reachable regions, only an area in near-equatorial latitudes, at 300° , there is

451 a very limited area that exhibit the $A_{2\sigma}$ -index between 1 and 2. This region
452 is rather more reliable, because trajectories are more energetic with higher
453 touchdown speeds, therefore allow less propagation time for uncertainties.
454 The results for Didymoon suggest that, deployment aiming minimum touch-
455 down speeds may entail challenges, at least for given deployment model,
456 distance and navigation uncertainties, that may be hard to overcome.

457 The deployments aiming minimum touchdown speeds to 1996 FG3-B sur-
458 face appears to be more robust, although again in a reduced region. The
459 most reliable region appears to be around the same region as observed in
460 Didymoon. However, unlike the Didymoon case, this region extends about
461 20° in both latitudinal and longitudinal directions. This robust region was
462 previously identified for the hypothetical asteroid in Çelik and Sánchez [15],
463 whose size is closer to 1996 FG3 (though slightly smaller) [15]. The existence
464 of the same region in both binaries implies a first hand estimation about the
465 reliable landing operations regardless of the target properties, even before
466 generating a global map.

467 Investigating the minimum touchdown speeds allows us to understand
468 the limits of this particular mission design problem. This information is un-
469 doubtedly valuable during a mission design process. However, the minimum
470 touchdown speeds do not always imply the optimal landing operations, as
471 demonstrated in Fig. 6. It follows then that larger touchdown speeds than
472 the minimum shall be attempted. A larger than the minimum touchdown
473 speed implies a much faster descent trajectory, thus shorter landing opera-
474 tions. With a straightforward reasoning, initial errors at the instant of de-
475 ployment may have lesser time to propagate, hence have a smaller impact on

476 the dispersion. Nevertheless, the spring error is proportional to the velocity
 477 magnitude, and thus the latter statement requires to be demonstrated.

478 As discussed in Section 3.1, $\epsilon = 0.7$ is defined as the maximum allowed
 479 value. Hence, a landing operation that precisely match this value is com-
 480 puted. That means to scale landing speeds, so that the energy damping at
 481 the instant of touchdown will ensure precisely the velocity magnitude that
 482 closes the ZVS at L1 point and restrict the motion around the secondary
 483 body. The maximum allowed touchdown speeds can therefore be as in Eq. 9
 484 for each landing point:

$$v_{T/D}^{site} = \frac{v_{L1}^{site}}{\epsilon} \quad (9)$$

485 where $v_{T/D}^{site}$ is touchdown speed and v_{L1}^{site} is the speed that closes the ZVS
 486 at the L1 point at a given landing site. $v_{T/D}^{site}$ is considered as the nominal
 487 touchdown speed for this case, and since ϵ value is conservatively defined,
 488 no margin has been assumed. Figure 7 now shows the robustness of those
 489 trajectories computed for the landing speeds as computed in Eq. 9, to the
 490 same errors in deployments as described in Table 2.

491 Note that the color code is now different, and separated as the $A_{2\sigma}$ -
 492 index values changed. The figure demonstrates a dramatic increase in the
 493 reliability of deployments to both targets. Total area of possible landing
 494 sites have clearly expanded in both asteroids, about $\sim 30\%$ of all 1996 FG3-B
 495 surface and $\sim 17\%$ of all Didymoon surface is now available for deployments
 496 with the introduced deployment model.

497 Despite the increased possibilities for deployments on Didymoon surface,
 498 no target site with $A_{2\sigma} < 1$ is observed. The lowest value in this case is 1.29,

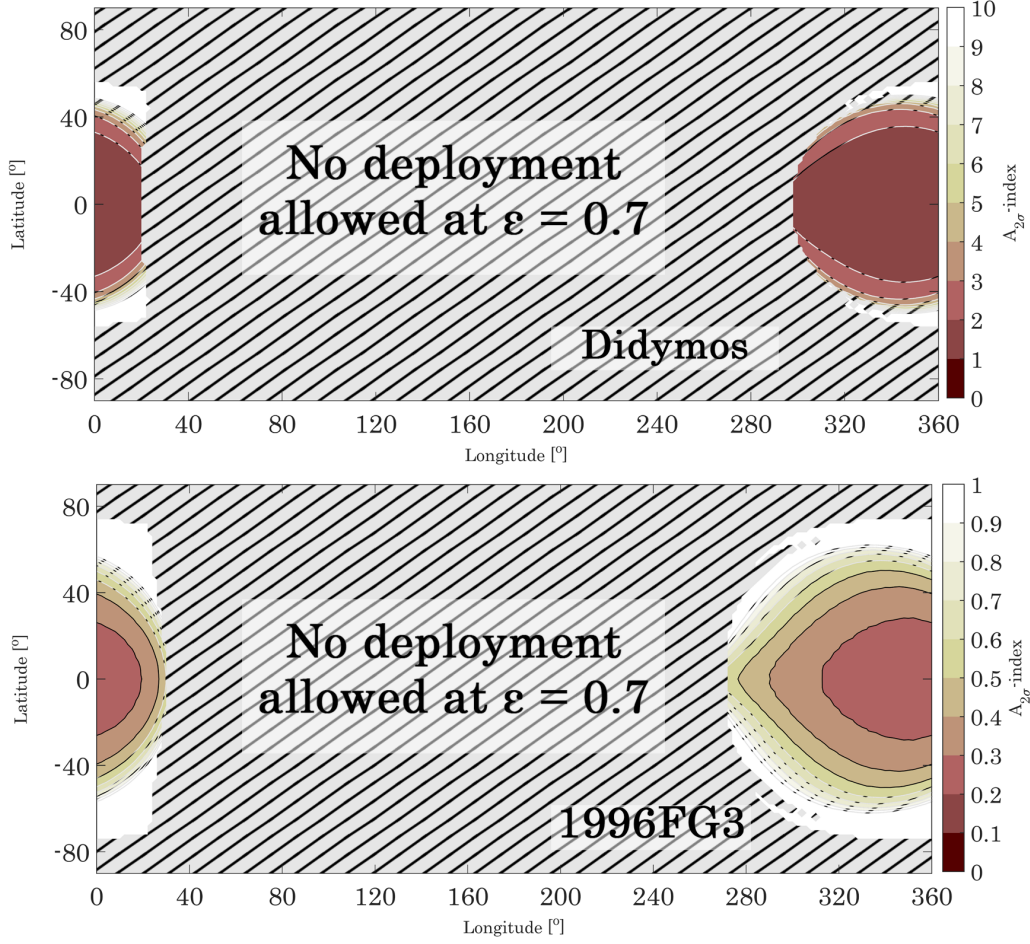


Figure 7: $A_{2\sigma}$ -index for modified touchdown speeds

499 and it is observed in equator at 334° longitude. The $A_{2\sigma}$ -index values remain
 500 in between 1 to 2 times the cross sectional area of Didymoon for a wide region,
 501 extending longitudes from 300° to 20° and latitudes up to 35° . This regions
 502 would provide the highest reliability, though still with lower than what would
 503 be expected from a reliable deployment ($A_{2\sigma} \ll 1$). This result suggests that
 504 the introduced deployment model, especially the deployment distance may

505 be responsible for this poor reliability in the Didymos case. Deployments
 506 at lower altitude will likely to improve the reliability of landing. Finally, as
 507 target latitude increases, reliability of deployments decreases. Mid-latitudes
 508 display the lowest reliability with $A_{2\sigma}$ -index ≥ 10 .

509 Deployments on the 1996 FG3-B surface, on the other hand, provides
 510 much more reliable prospects with a much larger area of landing opportu-
 511 nities. All possible regions have now shown $A_{2\sigma} < 1$, except small regions
 512 in high-latitudes. The lowest $A_{2\sigma}$ value is computed for 1° latitude and 0°
 513 longitude (i.e. approximately the tip of 1996FG3-B on the far side) as 0.24.
 514 $A_{2\sigma}$ -index values smaller than 0.6 extend between 280° in the trailing edge to
 515 20° in the leading edge, providing a numerous deployment opportunities that
 516 are reliable. Unlike for the Didymoon case, there are still reliable opportu-
 517 nities at mid-latitudes, up to approximately 45° - 50° . This opens up possibly
 518 interesting regions to be explored by a small lander, for the sizes of asteroid
 519 moons as 1996 FG3-B.

520 The $A_{2\sigma}$ -index offers quick assessment capability for a target landing site
 521 with a very simple parameter. However, it is reasonable to verify how our
 522 covariance based fast reliability analysis matches with Monte Carlo analyses,
 523 which can account nonlinearities intrinsic to the dynamical model. Therefore,
 524 Monte Carlo analysis was performed for each target landing locations in
 525 order to verify the assertions made here about the reliability of deployments
 526 with the $A_{2\sigma}$ -index. The Monte Carlo analysis in this case constitutes 1000
 527 randomly generated samples with the uncertainty values provided in Table
 528 2. It is important note that, a Monte Carlo analysis with 1000 samples
 529 represent statistics with $\sim 5\%$ error 3σ variance [37]. Furthermore, while the

530 $A_{2\sigma}$ -index computation took ~ 6 hours in total for this case, the Monte Carlo
 531 computations for this case took ~ 3 days for the same case for one hemisphere
 532 of one asteroid. The results are presented in Fig. 8.

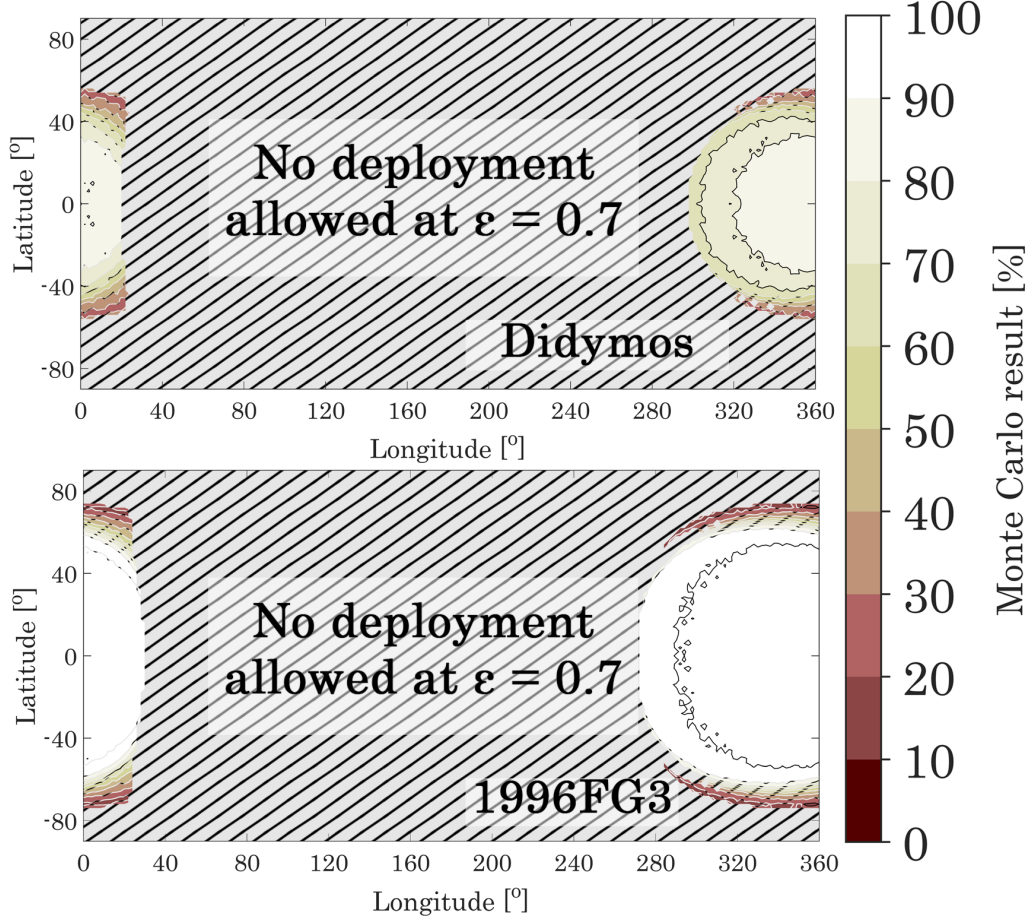


Figure 8: The Monte Carlo results.

533 In general, there is a very good agreement with our Monte Carlo analysis
 534 and $A_{2\sigma}$ -index results. Almost all regions in the 1996 FG3-B surface with
 535 $A_{2\sigma}$ -index lower than 1 show Monte Carlo success rate greater than 95%. The
 536 Monte Carlo analysis of the target site with the highest $A_{2\sigma}$ -index certifies

537 that the probability of first touchdown is 100%. In fact, it appears that very
 538 high $A_{2\sigma}$ values can be evaluated as reliable for the 1996 FG3-B surface, since
 539 the $A_{2\sigma}$ -index of up to 0.8 in the 1996FG3 case exhibits Monte Carlo success
 540 of greater than 90%. If we then assume a coefficient of restitution of 0.7 or
 541 lower, one can be confident that the lander will remain in the surface of 1996
 542 FG3-B, or binary systems whose properties similar to that.

543 The situation, on the other hand, is much more complex in Didymoon sur-
 544 face. While the $A_{2\sigma}$ -index is distributed homogeneous in a relatively larger
 545 area in Fig. 7, Monte Carlo results for the same region reveal a fragile
 546 condition. Indeed, our assertions for Didymoon was confirmed, and the de-
 547 ployments to Didymoon surface is not at all reliable against the initial errors
 548 with the assumption made. It appears that the $A_{2\sigma}$ -index is less accurate for
 549 a smaller binary according to the Monte Carlo results, but always in agree-
 550 ment with it qualitatively. In this respect, the $A_{2\sigma}$ -index works well. The
 551 results, on the other hand, suggest that, when the uncertainties are the same,
 552 the deployment distance must be closer to the Didymoon surface for more
 553 reliable operations.

554 As a side note, although it is not explored in this work, it should also be
 555 noted about the Monte Carlo analysis that allowing longer propagation time
 556 (>12 h) and higher number of samples in simulations may slightly alter the
 557 presented success probabilities of the first touchdowns on both targets.

558 5. Conclusions

559 This paper investigated the reliability of ballistic landings on the secon-
 560 daries of two previously proposed target binaries, Didymos and 1996 FG3.

561 Building a model on top of the previously developed algorithm [15], various
562 simulations were performed in order to assess statistical success of nominal
563 trajectories under the effect of deployment and navigation errors. It was
564 found that, landing trajectories to the regions with lowest possible touch-
565 down speeds are unavailable for short duration of deployment operations,
566 therefore prone to suffer from uncertainties. A simple scale-up procedure is
567 applied to touchdown speeds in order to increase their energy by means of
568 assuming a new, conservative coefficient of restitution, whose value is in har-
569 mony with observational findings and theoretical studies. Allowing higher
570 touchdown speeds have greatly increased the reachable area and reliability
571 of deployment operations for given deployment model.

572 A covariance analysis was performed with realistically defined uncertain-
573 ties in order to assess the robustness of the available trajectories. Reliable
574 regions are identified via a simple index defined by the projected area of
575 the uncertainty ellipsoid in the topocentric frame of the target landing sides,
576 and cross-sectional area of the target asteroid. This simple index is a useful
577 measure, despite its simplicity, and allows a quick qualitative investigation
578 of robust landing operations. The usefulness of the index is in fact certified
579 by the Monte Carlo analysis. Thus, the robust design optimization of such
580 mission can easily include this covariance based reliability index, which can
581 provide sufficiently accurate reliability results to be used in the process.

582 The deployment reliability within the available regions are much higher in
583 the far side of the binary moons, with very small deployment speeds. Near-
584 equatorial regions are by far the most robust, with more longitudes in the
585 trailing side. Larger binary moons, at least sizes on the order of 1996FG3

586 or more, also provide opportunities to explore higher latitude regions, which
587 might be of interest to understand the binary formation. The deployment
588 operations for mid- and high-latitudes, however, seem to be much less reliable
589 in small binaries with the proposed deployment strategy. Particularly, there
590 are no deployment opportunities identified for polar latitudes in both sample
591 asteroids. However, the reliability analysis in this paper suggests that, in
592 order to achieve higher impact probabilities in smaller asteroid cases, a more
593 accurate deployment mechanism and navigation system in motherships, and
594 closer deployments are paramount. However, it should be noted that for the
595 latter, that dynamical stability of mothership motion and operational risk
596 due to the proximity to the surface must carefully be assessed.

597 The analyses in this paper revealed regions of reliable ballistic landing
598 through the covariance-based reliability index. This index would provide a
599 simple, straightforward and efficient analysis framework. The results of that
600 can also be used in the robust optimization of the deployment and descent
601 operations where the reliability of the landing trajectory is also maximized in
602 the design process. The final results on the target binary asteroids would also
603 provide useful inputs to the current and the future small body exploration
604 missions that carry small landers to be deployed to the surface via ballistic
605 trajectories.

606 **Acknowledgement**

607 Onur Celik acknowledges MEXT research scholarship from Japanese gov-
608 ernment and short-term research grant from ROB. The authors would like
609 to thank Massimo Casasco for his valuable inputs about the navigation and

610 deployment errors.

611 References

- 612 [1] J. L. Margot, M. C. Nolan, L. A. M. Benner, S. J. Ostro, R. F.
613 Jurgens, J. D. Giorgini, D. B. Campbell, Binary asteroids in the
614 near-Earth object population, *Science* 296 (5572) (2002) 1445–1448.
615 doi:10.1126/science.1072094.
- 616 [2] A. W. Harris, M. A. Barucci, J. L. Cano, A. Fitzsimmons,
617 M. Fulchignoni, S. F. Green, D. Hestroffer, V. Lappas, W. Lork,
618 P. Michel, D. Morrison, D. Payson, F. Schäfer, The European Union
619 funded NEOShield project: A global approach to near-Earth object
620 impact threat mitigation, *Acta Astronautica* 90 (1) (2013) 80–84.
621 doi:10.1016/j.actaastro.2012.08.026.
- 622 [3] J. P. Sanchez, C. Colombo, Impact hazard protection efficiency by a
623 small kinetic impactor, *Journal of Spacecraft and Rockets* 50 (2) (2013)
624 380–393. doi:10.2514/1.A32304.
- 625 [4] M. A. Barucci, A. F. Cheng, P. Michel, L. A. M. Benner, R. P.
626 Binzel, P. A. Bland, M. Zolensky, MarcoPolo-R near earth asteroid sam-
627 ple return mission, *Experimental Astronomy* 33 (23) (2012) 645–684.
628 doi:10.1007/s10686-011-9231-8.
- 629 [5] R. C. Anderson, D. Scheeres, S. Chesley, the BASiX Science Team, A
630 Mission Concept to Explore a Binary Near Earth Asteroid System, in:
631 Proceedings of the 45th Lunar and Planetary Science Conference, The
632 Woodlands, Texas, 2014, March 17–21, Paper number 1777.

- 633 [6] A. F. Cheng, J. Atchison, B. Kantsiper, A. S. Rivkin, A. Stickle,
634 C. Reed, S. Ulamec, Asteroid Impact and Deflection Assessment
635 mission, *Acta Astronautica* 115 (OctoberNovember) (2015) 262–269.
636 doi:10.1016/j.actaastro.2015.05.021.
- 637 [7] A. G. I. Carnelli, R. Walker, Science by Cubes: Opportunities to In-
638 crease AIM Science Return, in: *Proceedings of the 4th Interplanetary*
639 *CubeSat Workshop*, London, UK, 2015, May 27–28, Paper number
640 2015.B.3.1.
- 641 [8] O. Karatekin, D. Mimoun, N. Murdoch, B. Ritter and N. Gerbal, The
642 Asteroid Geophysical EXplorer (AGEX) to Explore Didymos, in: *Pro-*
643 *ceedings of the 5th Interplanetary CubeSat Workshop*, Oxford, UK, 2016,
644 May 28–29, Paper number 2016.A.2.1.
- 645 [9] S. Ulamec, L. O’Rourke, J. Biele, B. Grieger, R. Andres, S. Lodiot,
646 P. Munoz, A. Charpentier, S. Mottola, J. Knollenberg, M. Knapmeyer,
647 E. Kuhrt, F. Scholten, K. Geurts, M. Maibaum, C. Fantinati, O. Kuche-
648 mann, V. Lommatsch, C. Delmas, E. Jurado, R. Garmier, T. Mar-
649 tin, Rosetta Lander - Philae: Operations on comet 67P/Churyumov-
650 Gerasimenko, analysis of wake-up activities and final state, *Acta Astro-*
651 *nautica* 137 (August) (2017) 38–43. doi:10.1016/j.actaastro.2017.04.005.
- 652 [10] S. Tardivel, D. J. Scheeres, Ballistic Deployment of Science Packages on
653 Binary Asteroids, *Journal of Guidance, Control, and Dynamics* 36 (3)
654 (2013) 700–709. doi:10.2514/1.59106.
- 655 [11] S. Tardivel, P. Michel, D. J. Scheeres, Deployment of a lander on the

- 656 binary asteroid (175706) 1996 FG₃, potential target of the european
657 MarcoPolo-R sample return mission, *Acta Astronautica* 89 (August–
658 September) (2013) 60–70. doi:10.1016/j.actaastro.2013.03.007.
- 659 [12] S. Tardivel, C. Lange, S. Ulamec, J. Biele, The Deployment of
660 MASCOT-2 to Didymoon, in: *Proceedings of the 26th AAS/AIAA Space*
661 *Flight Mechanics Meeting*, Napa, California, 2016, February 14–18, Pa-
662 per number: AAS 16-219.
- 663 [13] S. Tardivel, Optimization of the Ballistic Deployment to the Secondary
664 of a Binary Asteroid, *Journal of Guidance, Control, and Dynamics*
665 39 (12) (2016) 2790–2798. doi:10.2514/1.G000593.
- 666 [14] F. Ferrari, M. Lavagna, Consolidated phase a design of Asteroid Impact
667 Mission: MASCOT-2 landing on binary asteroid didymos, *Advances in*
668 *the Astronautical Sciences* 158 (October) (2016) 3759–3769.
- 669 [15] O. Çelik, J. P. Sanchez, Opportunities for Ballistic Soft Landing in Bi-
670 nary Asteroids, *Journal of Guidance, Control, and Dynamics* 40 (6).
671 doi:10.2514/1.G002181.
- 672 [16] J. P. Sánchez, D. García Yarnoz, C. McInnes, Near-Earth asteroid
673 resource accessibility and future capture mission opportunities, in:
674 *Global Space Exploration Conference*, International Astronautical Fed-
675 eration, Washington, USA, 2012, May 22–24. Paper number: GLEX-
676 2012.11.1.5x12412.
- 677 [17] V. Szebehely, *Theory of Orbits*, Academic Press: New York, 1967.

- [18] S. Tardivel, D. J. Scheeres, P. Michel, S. van Wal, P. Sanchez, Contact Motion on Surface of Asteroid, *Journal of Spacecraft and Rockets* 51 (6) (2014) 1857–1871. doi:10.2514/1.A32939.
- [19] S. Ulamec, C. Fantianti, M. Maibaum, K. Geurts, J. Biele, S. Jansen, L. O’Rourke, Rosetta Lander–Landing and Operations on Comet 67P/Churyumov–Gerasimenko, *Acta Astronautica* 125 (August–September) (2016) 80–91. doi:10.1016/j.actaastro.2015.11.029.
- [20] H. Yano, T. Kubota, H. Miyamoto, T. Okada, D. Scheeres, Y. Tagagi, K. Yoshida, M. Abe, S. Abe, O. Barnouin-Jha, Touchdown of the Hayabusa Spacecraft at the Muses Sea on Itokawa, *Science* 312 (5778) (2006) 1350–1353. doi:10.1126/science.1126164.
- [21] J. Biele, S. Ulamec, M. Maibaum, R. Roll, L. Witte, E. Jurado, P. Munoz, W. Arnold, H.-U. Auster, C. C. et al., The Landing(s) of Philae and Inferences About Comet Surface Mechanical Properties, *Science* 349 (6247) (2015) 1–6. doi:10.1126/science.aaa9816.
- [22] J. Biele, L. Kessler, C. D. Grimm, S. Schröder, O. Mierheim, M. Lange, T.-M. Ho, Experimental Determination of the Structural Coefficient of Restitution of a Bouncing Asteroid LanderarXiv:1705.00701.
URL <http://arxiv.org/abs/1705.00701>
- [23] T. Ho, J. Biele, C. Lange, AIM MASCOT-2 Asteroid Lander Concept Design Assessment Study, Tech. rep., German Aerospace Center (DLR) (2016).

- 700 [24] S. Sawai, J. Kawaguchi, D. J. Scheeres, N. Yoshikawa, M. Ogasawara,
701 Development of a Target Marker for Landing on Asteroids, *Journal of*
702 *Spacecraft and Rockets* 51 (4) (2014) 1857–1871. doi:10.2514/2.3723.
- 703 [25] T. Kubota, S. Sawai, T. Hashimoto, J. Kawaguchi, Collision dynamics
704 of a visual target marker for small-body exploration, *Advanced Robotics*
705 51 (14) (2014) 1857–1871. doi:10.1163/156855307782227426.
- 706 [26] O. Çelik, J. P. Sanchez, O. Karatekin, B. Ritter, Analysis of nat-
707 ural landing trajectories for passive landers in binary asteroids : A
708 case study for (65803) 1996GT Didymos, in: 5th Planetary Defence
709 Conference, 2017, May 15–19. Paper number: IAA-PDC17-03-P03.
710 doi:10.13140/RG.2.2.34443.90405.
- 711 [27] L. Dell’Elce, N. Baresi, S. Naidu, L. Benner, D. Scheeres,
712 Numerical investigation of the dynamical environment of 65803
713 Didymos, *Advances in Space Research* 59 (5) (2016) 1304–1320.
714 doi:10.1016/j.asr.2016.12.018.
- 715 [28] F. Damme, H. Hussmann, J. Oberst, Spacecraft orbit lifetime within
716 two binary near-Earth asteroid systems, *Planetary and Space Science*-
717 doi:10.1016/j.pss.2017.07.018.
- 718 [29] R. Walker, D. Binns, I. Carnelli, M. Kueppers, A. Galvez, CubeSat Op-
719 portunity Payload Intersatellite Network Sensors (COPINS) on the ESA
720 Asteroid Impact Mission (AIM), in: Proceedings of the 5th Interplane-
721 tary CubeSat Workshop, Oxford, UK, 2016, may 24–25. Paper number
722 2016.B.1.2.

- 723 [30] G. Gomez, A. Jorba, J. J. Masdemot, C. Simo, Study of the Transfer
724 from the Earth to a Halo Orbit Around the Equilibrium Point L1 56 (4)
725 (1992) 541–562.
- 726 [31] O. Çelik, O. Karatekin, B. Ritter, J. P. Sanchez, Reliability Analysis
727 of Ballistic Landing in Binary Asteroid 65803 (1996GT) Didymos un-
728 der Uncertainty and GNC Error Considerations, in: 26th International
729 Symposium on Spaceflight Dynamics, Vol. ists14, Matsuyama, Japan,
730 2017, Paper number: a90510.
- 731 [32] F. Ferrari, M. Lavagna, Ballistic landing design on binary aster-
732 oids: The AIM case study, *Advances in Space Research* (2017) 1–
733 16doi:10.1016/j.asr.2017.11.033.
- 734 [33] E. Canalias, A. Blazquez, E. Jurado, T. Martin, Philae Descent Tra-
735 jectory Computation and Landing Site Selection on Comet Churymov-
736 Gerasimenko, in: *Proceedings of 23rd International Symposium on*
737 *Spaceflight Dynamics*, Pasadena, California, 2012, Oct 29–Nov 2. Pa-
738 per number GC-2.
- 739 [34] J.-P. Sanchez, O. Çelik, Landing in Binary Asteroids : A Global Map
740 of Feasible Descent Opportunities for Unpowered Spacecraft, in: *In-*
741 *ternational Astronautical Congress (IAC)*, Adelaide, Australia, 2017,
742 September 25–29. Paper number: IAC-17,C1,8,7,x37745.
- 743 [35] M. Casasco, J. Gil-Fernandez, G. Ortega, I. Carnelli, Guidance Naviga-
744 tion and Control Challenges for the ESA Asteroid Impact Mission, in:

- 745 30th International Symposium on Space Science and Technology (ISTS
746 2017), Matsuyama, Japan, 2017, pp. 1–6.
- 747 [36] W. E. Wiesel, Modern orbit determination, Aphelion Press, 2003.
- 748 [37] M. Ceriotti, J. P. Sanchez, Control of asteroid retrieval trajec-
749 ries to libration point orbits, *Acta Astronautica* 126 (2016) 342–353.
750 doi:10.1016/j.actaastro.2016.03.037.



DSpace

<https://dspace.org/>

A comparative reliability analysis of ballistic deployments on binary asteroids

Çelik, Onur; Sánchez, Joan-Pau; Karatekin, Özgür; Ritter, Birgit

2018-03-14

Elsevier

<http://dx.doi.org/10.1016/j.actaastro.2018.03.020>

Çelik O, Sánchez JP, Karatekin Ö, Ritter B, A comparative reliability analysis of ballistic deployments on binary asteroids, Acta Astronautica, Volume 156, Issue March 2018, pp. 308-316