# Impactor-Observer Asteroid Lander Mission Concept for Emirates Mission to the Asteroid Belt (EMA)

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## *ABSTRACT*

The work presents an asteroid probe concept proposed for Emirates Mission to the Asteroid Belt (EMA) within Planet X Asteroid Lander Challenge. The top level requirements of the prob mission specify the initial conditions for the lander separation from the MBR Explorer, limit probe size to a cylinder of 30 cm in radius and height, limit its mass to 8.5 kg, and mandating the absence of both propulsion system and solar panels on board the probe.

The initial conditions for lander separation from the MBR Explorer are such that the lander is to be released from the main spacecraft orbit apoapsis with the radius of 80.5 km and associated flight path angle up to 45 degrees at touchdown following ballistic descent trajectory. In comparison to the previous asteroid probe missions the target asteroid has significantly greater gravitational parameter and the probe will be release at a higher altitude. Therefore, the uncontrolled descent trajectory of the lander results in a significantly high touchdown velocity of around 15 m/s, given the specified separation conditions

To ensure soft touchdown of the probe and consecutive in-situ scientific measurements we propose impactor-observer concept where the probe is to be comprised of the main part - observer equipped with scientific instruments and attitude determination and control system and auxiliary part - impactor which is to be used for velocity dumping during the lander descent.

## I. Introduction

Landing on asteroids is a highly valuable mission from a scientific point of view, however, it is accompanied by significant engineering challenges. The dynamic environment and the exact shape of small bodies are not well known which makes a priory design of close proximity operations such as landing difficult. For example, the gravitational field of asteroids and comets is weak and non-uniform compared to large planetary bodies. This means that the orbits around these bodies are potentially unstable, and the low gravitational force could make soft-landing without bouncing challenging. In addition, the irregular shape of these bodies makes it difficult to pre-determine the landing trajectory precisely. On the other hand, asteroids and comets are located far away from the Earth, resulting in a significant delay in communication between the ground station on Earth and the spacecraft. Therefore, achieving real-time descent control from the ground station is nearly impossible. As a result, autonomous onboard control systems are used to execute the landing maneuver.

The paper elaborates on proposal for Startup Lander Challenge Planet X organized by UAE Space Agency [1] in November 2023. The concept has been developed in Propulsion and Space Research Center (PSRC) at Technology Innovation Institute (TII). The following objectives have been stated by the competition:

- Design and development of the lander to be launched from the Mohammed Bin Rashid (MBR) Explorer Spacecraft, and the implementation of the landing process on the seventh asteroid of the mission. The explorer must be able to collect data from the surface of the asteroid by means of a scientific instrument to collect measurements in-situ.
- The lander must demonstrate innovative landing, navigation, communications and sample collection technologies. The design should prioritize safety, efficiency and resilience to the deep space environment.

### *Emirates Mission to the Asteroid Belt (EMA) and Target Asteroid*

According to the publicly available data on EMA mission [2; 3] the MBR explorer will fly by six asteroids, after which it will deploy a lander to the final asteroid. Meanwhile, the main spacecraft will remain in orbit around the asteroid. The asteroid to land is 269 Justitia [4] - a relatively small (50.7 km in diameter) Ld-type Main Belt Asteroid orbiting near to ecliptic with a period of about 4.2 years (see Fig.1). Thus, the lander will travel on-board the mother spacecraft for about 8 years before the bargaining of its mission in the vicinity of Justitia asteroid.

Justitia has an average diameter $r_J = 25.36$ km and gravitational parameter $\mu_J = 4.37 \cdot 10^{-3} \frac{km^3}{s^2}$ [5]. Let's consider spherically symmetrical gravitational potential model for the preliminary mission analysis. The asteroid

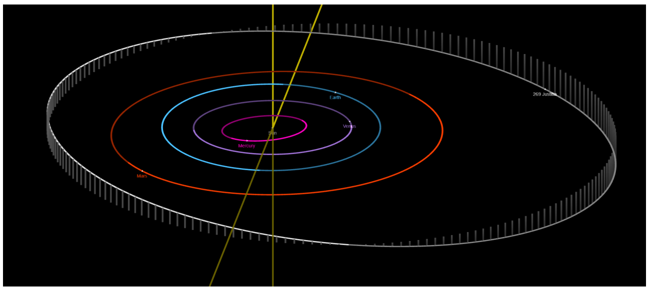

Figure 1: Asteroid 269 Justitia heliocentric orbit [4]

has a period of self rotation $T = 33.128$ hours, escape velocity at surface level $v_{esc} = \sqrt{\frac{2\mu_J}{r}} = 18.6$ m/s and Hill sphere radius defining the region of a small body attraction dominance $r_{Hill} = a_J(1 - e_J)(\frac{m_J}{3m_\odot})^{1/3} = 6.8 \cdot 10^3$ km. Table 1 lists Justitia's orbit elements given with respect to the sun-centered inertial ecliptic frame J2000 for a corresponding epoch. A detailed shape model of the asteroid is available in [6].

Table 1: Asteroid Justitia orbit

| Orbit element | Value | Unit |
|---|---|---|
| semi-major axis, $a$ | 2.6184 | AU |
| eccentricity, $e$ | 0.2139 | - |
| inclination, $i$ | 5.474 | deg |
| RAAN, $\Omega$ | 156.666 | deg |
| AOP, $\omega$ | 119.997 | deg |
| Mean anomaly, $M$ | 104.626 | deg |
| Epoch, $T$ | 2460200.5 | JD |

## II. Impactor-Observer Asteroid Lander Mission Concept

The proposed lander system for the concept is designed to satisfy two challenging requirements:

- survival of touchdown velocity $v_t > 10$ m/s,
- capture images of asteroid during descent and transfer the images to the main spacecraft.

In order to satisfy the impact velocity constraint, the lander system proposed to comprise of two modules:

- scientific module or observer,
- impactor.

The primary concept behind dividing the lander into two segments is to meet the necessary touchdown velocity by employing the principle of momentum exchange between the observer and the impactor (see Fig. 2) . The two parts will remain attached to each other while the lander is housed inside the MBR explorer and after deployment. The separation between the observer and the impactor will occur at a specified altitude above the surface of the asteroid.

Given that the observer is the part that will land softly on the surface of the asteroid, it has to carry the major subsystems and payloads. The observer will be equipped with an on-board computer system (OBC), antenna and transceiver for the uplink channel with the MBR explorer, battery packs, electric power distribution system (EPS) and attitude control system including star tracker and 3-axis reaction wheels. Fine attitude control is essential for aligning the camera for imaging purposes and orienting the lander system prior to the separation of the impactor. The objectives of the observer is as follows:

- Capture images for the asteroid at different altitude.
- Land softly on the surface of the asteroid.
- Perform in-situ observation and data collection.
- Collect and transmit data to MBR spacecraft.
- Use mobility mechanism to move around the asteroid and discover different areas if possible.

On the other hand, the impactor is the part that will be used mainly to slow down the observer. Therefore, the impactor must have a reasonable mass to perform the momentum exchange concept. A dummy mass structure can be used to achieve this goal. The following points summarize the objectives that should be achieved by the impactor:

- Damp the velocity of the observer following momentum exchange concept.
- Impact the surface of the asteroid with high velocity making a small crater.

However, the dummy mass can be replaced with some components or payloads to meet certain objectives. For example, a secondary battery pack could be housed within the impactor to power the subsystems on the observer prior to separation. Furthermore, a small camera can be integrated into the impactor to capture images of the asteroid. These images can then be transmitted to the observer using short-range antenna.

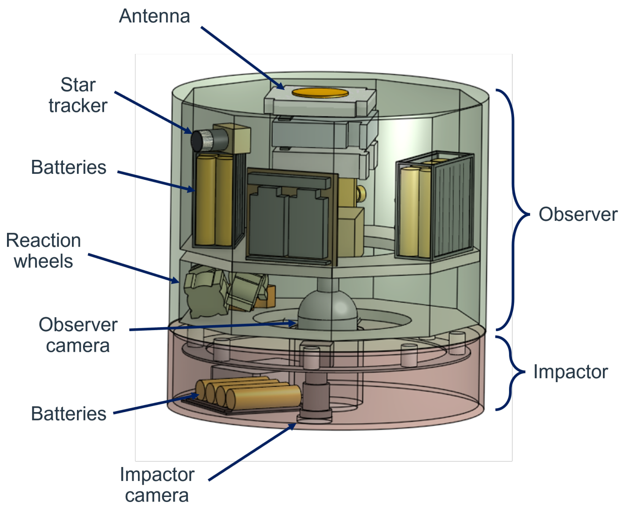

Figure 2: Impactor-Observer preliminary 3D model

## III. Descent Trajectory Design

The trajectory of the lander is analyzed under various initial conditions, considering the given deployment altitude and surface touchdown flight path angle. This analysis is crucial for applying the momentum exchange principle accurately during the mission.

### *Ballistic descent*

The lander descent flight geometry is depicted in Fig. 3. It is to be released from main spacecraft at apoapsis in a way guaranteeing lander's rendezvous with Justitia.

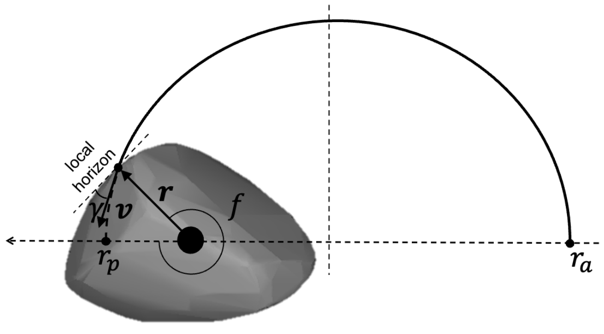

Figure 3: Lander descent geometry

According to the requirements of the Planet X Lander Competition, the lander is to be deployed from the main spacecraft's orbit apoapsis $r_a$, located at a distance of 80.5 km. The deployment velocity is defined such that the maximum absolute value of the flight path angle $\gamma$ at touchdown equal to 45 degrees.

The flight path angle (see Fig. 3) is the angle between local horizon or transverse direction and the velocity vector. It is defined as follows:

$$\gamma = sgn(\mathbf{r} \cdot \mathbf{v}) \arccos\left(\frac{h}{rv}\right), \tag{1}$$

where $\mathbf{r}$ and $\mathbf{v}$ are the lander position and velocity vectors respectively, and $h = |\mathbf{r} \times \mathbf{v}|$ is lander's orbit angular momentum.

In order to meet the constraint on the flight path angle at touchdown, the initial velocity of the lander should be within a certain range. Given that the lander will be deployed at apoapsis, the initial lander descent trajectory is defined only by the lander deployment velocity from the MBR spacecraft.

Let us find the the range of suitable descent trajectories numerically by varying initial lander velocity at apoapsis $v_a$. The maximum velocity at apoapsis corresponds to the critical case with flight path angle equal to zero. For this case, the perigee radius $r_p$ is equal to the asteroid radius.

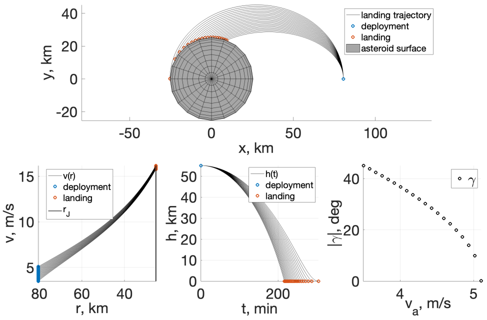

Figure 4: Landing profiles for different initial velocities at deployment

Figure 4 shows landing trajectories, velocity and altitude profiles for flight path angles at touchdown ranging from 0 to 45 degrees as mentioned in the requirements. As shown in the figure, the initial lander velocity at deployment $v_a$ should be in a range from 3.5 to 5.1 m/s to have appropriate flight path angle at touchdown. However, the impact velocity of the lander is more than 15 m/s if no maneuver is applied. Thus, the lander is most likely will crash on the surface of the asteroid during touchdown meaning no in-situ scientific measurements can be performed. Therefore, we propose to reduce the velocity of the lander using the impactor-observer concept. Additionally, the observer module can be outfitted with a deployable protective shield like the one in [7] to provide additional protection for the outer structure, subsystems, and payloads of the observer.

### *Descent with momentum exchange-based observer velocity damping*

In order to ensure soft observer touchdown on Justitia surface we consider the concept of observer momentum exchange with impactor via spring separation mechanism. Since the impactor will gain momentum after separation, its velocity at touchdown will be much grater than the observer velocity. Therefore, the impactor has the potential to produce a crater after collision that can reveal Justitia internal materials and structure which are important for exploration purposes. Therefore, there is a requirement to come up with separation conditions yielding impactor rendezvous with Justitia surface. Also, it is important to have a direct line-of-sight (LOS) between the impactor and the observer during final stage descent for enabling crater observations using observer camera.

The theorem on momentum $\mathbf{Q}$ change is used to define lander separation conditions:

$$\dot{\mathbf{Q}} = \frac{d}{dt}\sum_{i=1}^{n} m_i \mathbf{v}_i = \sum_{i=1}^{n} \mathbf{F}_i^{ext}. \tag{2}$$

The major considered parameters for the analysis are the following:

- observer-to-impactor mass ratio $m_r = \frac{m_o}{m_i}$
- separation altitude $h_s$
- observer and impactor touchdown velocities $v_o^{touchdown}$, $v_i^{touchdown}$
- observer and impactor descent time after separation $T_o^{descent}$, $T_i^{descent}$

As a preliminary analysis, let's consider a lander system with observer-impactor mass ratio of $m_r = 3$, yielding observer mass of $m_o = 6.375$ kg and impactor mass of $m_i = 2.125$ kg (the total mass must not exceed 8.5 kg as given in the requirements). Since the initial deployment velocity was not given in the requirements, let's consider a landing trajectory corresponding to 30 degrees flight path angle for uncontrolled motion. The lander mission concept of operation is demonstrated in Fig. 5.

The lander mission starts with lander deployment from the MBR spacecraft at an altitude of 80.5 km. After deployment, it performs asteroid surface imaging until it reaches separation altitude. Following a numerical and analytical analyses of the impactor release conditions we choose a separation altitude of $h_s = 2$ km. This altitude is suitable because it ensures a soft touchdown velocity for the observer and guarantees that the impactor will touch down on the surface of the asteroid. Additionally, it maintains a direct line of sight (LOS) between the impactor and the observer during the impactor's descent, thus making it possible to observe the impactor by the observer camera (see Fig. 6).

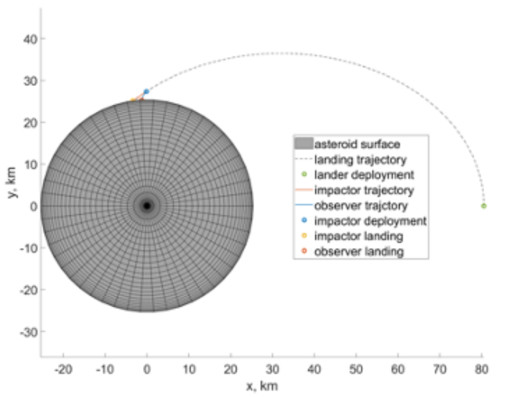

Figure 5: Landing trajectories for impactor and observer

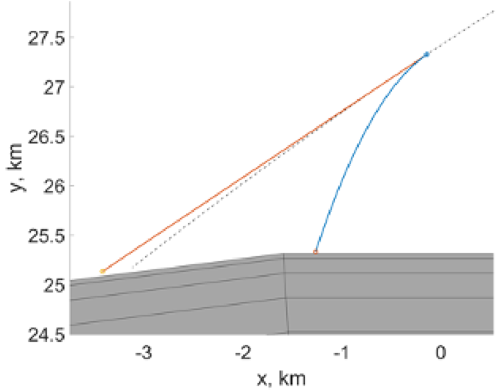

Figure 6: Descent trajectories after separation

Following the theorem of momentum change we defined the impactor deployment velocity of 39 m/s in the tangential direction of the landing ballistic trajectory. It guarantees observer's touchdown velocity $v_o^{touchdown} =$ 5 m/s. Figure 7 shows the altitude profile of the impactor and the observer after separation. The absolute velocity profile of the impactor and the observer are shown in Fig. 8. As mentioned, we propose to equip the observer with a protective shield as the landing velocity may still pose a risk to the structural integrity of the observer.

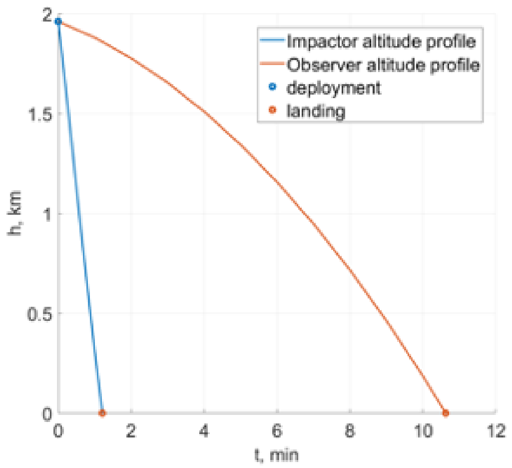

Figure 7: Altitude profiles

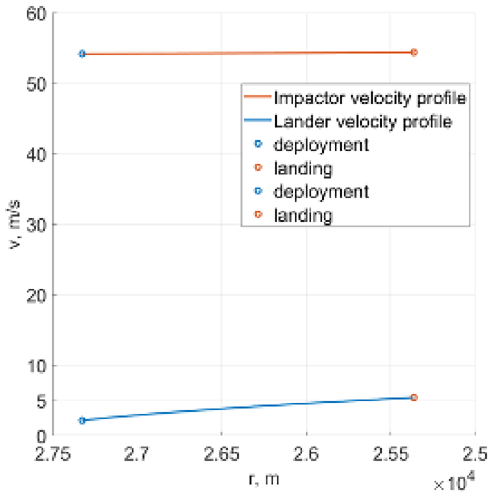

Figure 8: Velocity profiles

## IV. Conclusion

In this paper, the lander mission concept of operation is presented following the idea of momentum change principle to land softly on the surface of the asteroid. The lander is divided into two parts: the observer and the impactor where they will separate at certain altitude above the surface of the asteroid. The separation is done mainly to slow down the observer by deploying the impactor with a high velocity using springs. As a result, the observer will touchdown the surface of the asteroid softly while the impactor will have a harsh impact. The descent trajectory of the lander was analyzed to find the optimal separation altitude that will minimize the observer touchdown velocity and will ensure that the impactor will also impact the surface. Both observer and impactor descent altitude and velocity profiles are shown in the paper.

## References

[1] "Planet X, StartUp Asteroid Lander Challenge." `https://space.gov.ae/Page/20123/20281/Lander-Challenge-for-Startups--SMEs`.

[2] H. AlMazmi and et al, "Science Overview of the Emirates Mission to the Asteroid Belt," *Bulletin of the AAS*, vol. 55, oct 23 2023. https://baas.aas.org/pub/2023n8i107p01.

[3] S. Alhameli, F. and et al, "Mission design for the emirates mission to explore the asteroid belt," in *Asteroid, Comets, Meteors Conference*, 2023.

[4] "Solar System Dynamics, JPL, Asteroid Justitia parameters." `https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=Justitia`.

[5] J. W. McMahon and et. al, "Estimation of justitia's shape and gravity via the emirates mission to explore the asteroid belt," in *Asteroid, Comets, Meteors Conference*, 2023.

[6] J. Durech, V. Sidorin, and M. Kaasalainen, "DAMIT: a database of asteroid models," , vol. 513, p. A46, Apr. 2010.

[7] "Epfl's collapsable delivery drone protects your package with an origami cage." `https://spectrum.ieee.org/epfl-collapsable-delivery-drone-protects-you`