Mission Design for NEO Detection and Impact Warning System*

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On February 15th, 2013, a meteor with size of about 20 m in diameter entered the Earth’s atmosphere over Chelyabinsk, Russia, and exploded at an altitude of about 20 km, damaging about 4,500 buildings and injuring about 1,500 residents. This incident widely invoked an interest in hazard mitigation caused by a NEO. Motivated by such interests, this study focuses on a new concept of NEO detection and impact warning system. In this concept, a space telescope is placed at the L1 point of the Sun-Earth system to intensively observe the NEOs in-coming from the noon-side, which ground-based observatories hardly detect because of the sunlight. Throughout some cases of simulations, this paper reveals the distributions of NEO directions at detection, V-infinity vectors at the Earth impact, and the NEO orbit determination precision are evaluated.

Key Words: NEO (Near-Earth Object), V-infinity, Virtual Impactors, Orbit Determination, Impact Hazard Warning

Nomenclature

\[ a: \text{semi-major axis in au} \]
\[ b: \text{heliocentric latitude} \]
\[ \beta: \text{phase angle} \]
\[ d: \text{slant range in au} \]
\[ D: \text{diameter in kilometers} \]
\[ e: \text{eccentricity} \]
\[ \varepsilon: \text{ratio of light intensity} \]
\[ f: \text{true anomaly} \]
\[ G: \text{slope parameter} \]
\[ H: \text{absolute magnitude} \]
\[ i: \text{inclination} \]
\[ J: \text{detectable magnitude} \]
\[ \Delta J: \text{magnitude difference} \]
\[ l: \text{heliocentric longitude} \]
\[ P: \text{intersection point of Earth’s orbit and NEO’s orbit} \]
\[ r: \text{heliocentric distance} \]
\[ \Delta t: \text{integration time} \]
\[ V: \text{visual magnitude} \]
\[ \dot{V}: \text{velocity vector} \]
\[ \omega: \text{argument of periapsis} \]
\[ \sigma: \text{standard deviation} \]
\[ \mu: \text{gravitational constant} \]
\[ X: \text{X axis of coordinate system} \]
\[ Y: \text{Y axis of coordinate system} \]

Subscripts

\[ E: \text{Earth} \]
\[ \infty: \text{infinity} \]
\[ HCI: \text{heliocentric inertial frame} \]
\[ SEF: \text{Sun-Earth fixed frame} \]

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1. Introduction

The Near Earth Object, NEO, hazard mitigation is a growing interest. In fact, on February 4th, 2013, a NEO the size of about 20 m in diameter entered the Earth’s atmosphere over Chelyabinsk, Russia, and exploded at an altitude of about 20 km, damaging about 4,500 buildings and injuring about 1,500 residents.1,2) The impact energy was approximately 500 kilotons of TNT, which is about 30 times larger than that of the atomic bomb detonated over Hiroshima. As of today, it was the worst NEO hazard in the history of mankind.

Under such circumstances, this study addresses a hazardous NEO detection and impact warning system utilizing the Lagrange point of the Sun-Earth system.3) In this study, a space telescope is placed at a Lagrange point 1 (L1) and monitors NEOs in-coming to Earth. In contrast to the orbit around Earth such as the “dawn-dusk” orbit in which most of the current NEO survey telescopes are placed, L1 is 1.5 × 10^5 km away from Earth. Thus, the degradation of observation data, for example the degradation by the Earth’s surface or the Moon entering the field-of-view, FOV of the space telescope, is minimum. Additionally, L1 enables earlier impact warning because of the distance from Earth. The orbit of the NEO is determined by “angle-only” observation data. If the possibility of an Earth impact is deemed to be “high,” then the tracking of the NEO is handed-over to Earth-based radar sites (i.e., Arecibo or Goldstone) to determine the orbit more precisely and raise an impact alarm to persuade the residents of the estimated impact area to evacuate. Figure 1 shows the diagram of V-infinity of a NEO.

As shown in Fig. 1, the in-coming directions vary depending on the impact points (i.e., from the noon-side at P_1, or from the night-side at P_2). In this study, the detection of NEOs in-coming from the noon-side is focused on, because those NEOs are hard to be discovered by observatories from...
the Earth. In fact, the above-mentioned Chelyabinsk meteor approached from the noon-side, which made it difficult for us to identify it before its Earth approach and impact.

2. Virtual Earth Impactors

2.1. Overview

In this study, virtual Earth impactors, which are imaginary hazardous NEOs on collision courses with Earth, are randomly produced based on the debiased orbital distribution of NEO population developed by Bottke et al. (i.e., “Bottke model”). Figure 2 shows the distribution of the virtual impactors in an $a$–$e$ map. The total number of virtual impactors in this simulation is 24,527. As shown in Fig. 2, the population of the virtual impactors concentrates around a point where $a = 2$ au and $e = 0.5$ in the $a$–$e$ map.

Once the keplerian elements of the virtual impactors are determined, V-infinity vectors at Earth impact are described as follows:

$$\vec{V}_{\infty} = \frac{\mu_E}{a_E} \begin{bmatrix} \pm \sqrt{2 - \frac{a_E}{a} - \frac{a(1 - e^2)}{a_E}} \\
\frac{\sqrt{a(1 - e^2)/a_E \cos(i) - 1}}{\pm \sqrt{a(1 - e^2)/a_E \sin(i)}} \end{bmatrix}$$

(1)

where $a_E$ is the semi-major axis of Earth’s orbit (i.e., 1 au), and $a$, $e$ and $i$ are the semi-major axis, eccentricity and inclination of the NEO of interest. Note that the V-infinity vector described by Eq. (1) is in the Sun-Earth fixed coordinate of the epoch of interest, which is not a rotational frame.

As Eq. (1) indicates, there are four kinds of V-infinity vectors with respect to a combination of $a$, $e$ and $i$. The signs of $X$ and $Z$ components of Eq. (1) correspond to two kinds of eccentricity vectors, and the ascending or descending intersection points, respectively. When the inclination $i$ is assumed to be zero, the conditions for the intersection of Earth and NEO orbits are described as follows:

$$a(1 - e) \leq 1 \text{ au} \leq a(1 + e)$$

(2)

The uniform distribution of V-infinity in the $a$–$e$ map is shown in Fig. 3. The color legends in Fig. 3 correspond to the contour lines of the V-infinity vectors. The black dashed line indicates the boundary condition of Eq. (2). As shown in Fig. 3, V-infinity increases as the eccentricity increases.

2.2. Orbits of virtual impactors

In this study, the Earth impact location is fixed on the point where $(X_{HCI}, Y_{HCI}, Z_{HCI}) = (1 \text{ au}, 0, 0)^T$. The Earth’s orbit is assumed to be a perfect circular orbit with a radius of 1 au, and it is also assumed that the impactors’ orbits are two-body motion. The impactors’ orbits are propagated backwardly from the Earth impact point, and the propagation is stopped when the distance between the impactor and Earth reaches 1 au. Figure 4 shows example orbits of the virtual impactors in the heliocentric inertial frame. “NEOs 1–3” appearing in Fig. 4 correspond to “averaged V-infinity + 1σ,” “averaged V-infinity,” and “averaged V-infinity − 1σ,” respectively. “Chelyabinsk” corresponds to the orbit produced based on the estimated keplerian elements of the Chelyabinsk meteor. The major parameters of the orbits depicted in Fig. 4 are summarized in Table 1.

Figure 5 shows the example orbits as viewed in the Sun-Earth fixed frame. As shown in Fig. 5, NEO2 and Chelyabinsk approach the Earth from the night-side at first, come inside the Earth’s orbit, and then impact the Earth from the noon-side.
Figure 6 shows the history of slant range (i.e., the distance between the impactor and the Earth). “t = 0” is the epoch of the Earth impact. The “minus” sign of time means backward propagation from the Earth impact point. The green and orange arrows in Fig. 6 indicate the point at which NEO2 and Chelyabinsk come into the noon-side from the night-side, respectively.

2.3. Population of virtual impactors in telescopic view

As mentioned, the space telescope placed at the Sun-Earth L1 point monitors the in-coming impactors from the noon-side. Once the impactor is detected, the space telescope outputs the direction. In this study, the heliocentric latitude \( b \) and longitude \( l \) are employed to describe the direction of the impactor detected. The definition of the angles is shown in Fig. 7.

Figure 8 shows the motions of impactors detected in the simulated telescopic view. As shown in Fig. 8, the NEOs move from left to right in the view. This motion coincides with orbital motion as shown in Fig. 5.

Figures 9–11 show the distribution of impactors in the telescopic view at 0.7, 0.4 and 0.1 au slant ranges from the Earth, respectively. As the figures indicate, impactors move from left to right as shown in Fig. 8, and the distribution scat-
ters as impactors approach the Earth. Note that the distribution of NEOs in the Bottke model is provided on a coarse grid, hence there are some gaps in the map.

The characteristics shown in Figs. 9–11 are important from the perspective of the mission design. Because the survey area and detectable range are conflicting factors (i.e., the wider survey area reduces the integration time at each Field of View, (FOV)), which means a shorter detectable range, and vice-versa. These factors should be a trade-off.

On the other hand, Figs. 12–14 show the distribution of V-infinity at the Earth impacts of 0.7, 0.4 and 0.1 au, respectively. As shown in the figures, the V-infinity becomes larger when the in-coming direction becomes close to the Sun direction. This is because the eccentricity of an impactor’s orbit in-coming from the Sun direction is large. The “high” V-infinity significantly increases the Earth impact energy (i.e., possibly cause devastating damage). Hence, careful attention should be paid to the detection of impactors in-coming from the Sun direction.

3. Simulation of NEO Detection

3.1. Size and visual magnitude of NEO

The primary objective of the proposed mission concept is to monitor and detect small unknown NEOs such as the Chelyabinsk meteor. Hence, the size of the virtual impactors is unified as some value as shown later. The absolute magnitude, $H$, is described as follows:

$$H = 17.75 - 5 \log_{10} D$$

where $D$ is the diameter of the impactor in kilometers. On the other hand, the visual magnitude, $V$, is determined by the geometry of the Sun, the impactor and the telescope, which is described as follows:

$$V = 246 ©2016 JSASS$$
$V = H + 5 \log_{10}(d \cdot r) - 2.5 \log_{10}((1 - G)\Phi_1 + G\Phi_2)$

where $d$ is the distance in au between an impactor and telescope, $r$ is the heliocentric distance of an impactor in au, and $G$, the slope parameter which is surge in brightness, is set to be 0.15 in this study. $\Phi_1$ and $\Phi_2$ are the functions of phase angle $\beta$, which is described as follows:

$$\Phi_1 = \exp \left\{ -A_1 \left( \tan \left( \frac{\beta}{2} \right) \right)^{B_1} \right\}$$

where $A_1 = 3.33$, $A_2 = 1.87$, $B_1 = 0.63$ and $B_2 = 1.22$. Figure 15 shows the definition of phase angle $\beta$.

### 3.2. Detectable visual magnitude of NEO

From the definition of the apparent magnitude, the ratio of light intensity, $\varepsilon$, is described as follows:

$$\varepsilon^\Delta J = 100$$

On the other hand, the magnitude difference, $\Delta J$ between $\Delta t$ and 1 sec integration is described as the following:

$$\varepsilon^\Delta J = \frac{\Delta t}{1 \text{ sec}}$$

Thus, the following equation is obtained,

$$\Delta J = \frac{\log_{10}(\Delta t/1 \text{ sec})}{0.4} = \frac{\log_{10}(\Delta t/1 \text{ sec})}{0.4}$$

Consequently, the detectable magnitude $J$ is described as follows:

$$J = J_1 + \Delta J = J_1 + \frac{\log_{10}(\Delta t/1 \text{ sec})}{0.4}$$

where $J_1$ is the detectable magnitude at 1 sec integration.

However, noise caused by the zodiacal light should be considered from the perspective of real mission design. In this study, it is assumed that the detectable magnitude improves with the square root of the integration time. In this assumption, the detectable magnitude is described as follows:

$$J = J_1 + \frac{\log_{10}(\Delta t/1 \text{ sec})}{0.8}$$

### 3.3. Configuration of simulation

In this study, the sizes of the virtual impactors are unified to the same value (i.e., 25 m/50 m/140 m), as summarized in Table 2. These sizes are based on clarification in the reference paper.\(^{10}\)

For example, the estimated size of the Chelyabinsk meteor is 16–19 m,\(^{15}\) which caused an “air burst.” On the other hand, the size of the asteroid that produced the “Barringer Crater” located in Arizona is estimated to be about 40 m.\(^{10}\) The size of the “Barringer Crater” is about 1.2 km in diameter and 170 m in depth, which is classified as “local scale” impact.\(^{10}\) The estimated size of the well-known 1908 Tunguska impact event is also 30 to 50 m in diameter.\(^{10}\)

The detection of NEOs of more than 140 m in diameter is a major objective of the current space-guard survey. In fact, the US Congress has mandated that “NASA discovers 90 percent of all near-Earth objects 140 meters in diameter or greater by 2020”.\(^{10}\)

Two observation cases are assumed in this simulation to trade-off between the detectable range and survey area. Figure 16 shows the diagram of the survey area.

In this study, a visible telescope with a $2 \times 2$ square degrees FOV is assumed to be used as an NEO observation instrument of the telescope. Because the telescope cannot look at the Sun, a light shield hood is necessary. In this simulation, it is assumed that the length of the light shield hood is four times longer than the telescope aperture diameter, which produces a 15-degree Sun avoidance angle, as shown in Fig. 15. The 15-degree Sun avoidance angle corresponds to about 1.7% of the whole sky.

Case-1 observes the concentrated region with a 30-degree half-angle, in which the integration time per FOV is 125 sec. The center of the observation region of Case-1 is designated in the ecliptic plane. Conversely, Case-2 observes half of the sky around the Sun. The integration time per FOV of Case-2 is 17 sec. Table 3 summarizes the two observation cases.

In each case, the telescope surveys the observation region once per day. Based on the “angle-only” data, the orbit of the detected NEO is coarsely determined. If a high possibility of Earth impact is estimated, then the telescope tracks the NEO of interest regardless of the predetermined observation re-

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**Table 2. Clarification of NEOs.**

| Diameter | $H$  | Event          | Impact energy | Frequency  |
|----------|------|----------------|---------------|------------|
| 25 m     | 25.76| Air burst      | 1 MT\(^*\)    | 200 yr     |
| 50 m     | 24.26| Local scale    | 10 MT\(^*\)   | 2000 yr    |
| 140 m    | 22.02| Regional scale | 300 MT\(^*\)  | 30000 yr   |

\(^*\)Megatons in TNT equivalent.
3.4 Simulation

Based upon the configuration mentioned in the previous section, the simulation of NEO detection is conducted. In this simulation, the orbits of the virtual impactors are propagated backwardly from Earth impact and the propagation is stopped when the distance between the impactor and the Earth reaches 1 au, or TOF reaches "—1200 days." Then, the impactors' orbits are propagated forwardly (i.e., they come back toward the Earth). The visual magnitudes of impactors are computed each step and compared with thedetectable magnitude of the telescope. Once an impactor is detected, the accumulated number of detections is incremented.

Figure 17 shows the history of the accumulated number of detection in the case of $J_1 = 20$.

From a practical point of view, an impactor should be detected at a range sufficiently far enough from the Earth to estimate the impact area and to evacuate. In this study, the minimum detection range to satisfy the above-mentioned perspectives is assumed to be 0.2 au, at which a minimum TOF is about 1 week as shown in Table 5. Table 6 summarizes the accumulated number of detections at 0.2 au from the Earth. The numbers in the parenthesis are the percentage of the accumulated number of detections to the total number of the virtual impactors.

As shown in Table 6, the detection percentages of the impactors with a size of 25 and 50 m are less than 1%. Even in the case of 140 m, the percentage is less than 10%. Hence, apparently, $J_1 = 20$ is insufficient to satisfy the mission objective.

Next, Fig. 18 shows the history of the accumulated number in the case of $J_1 = 22$, and Table 7 summarizes the accumulated number at 0.2 au. When we compare the history of the accumulated number shown in Fig. 18, the results of Case-1 are mostly superior to those of Case-2. As summarized in Table 7, the detection percentages in the case of 140 m are about 40% of the total number of virtual impactors. Note that the telescope assumed in this study monitors the noon-side. Hence, roughly 80% of the impactors in-coming from the noon-side will be detected before they reach 0.2 au from the Earth if the size is more than 140 m. However, $J_1 = 22$ is still insufficient to detect impactors whose size is less than 50 m.
Finally, Fig. 19 shows the history of the accumulated number of detections, and Table 8 summarizes the accumulated number of detections at 0.2 au for the case of $J_1 = 24$.

As shown in Fig. 19, the results of Case-1 are superior to those of Case-2 in the case of 25 m/50 m, just like the results of $J_1 = 20, 22$. However, in the case of 140 m, the results of Case-2 are superior to those of Case-1. As summarized in Table 4, the detectable range in both Case-1 and Case-2 are more than 1 au; hence, a wider observation region results in a larger accumulated detection number.

As summarized in Table 8, a telescope of $J_1 = 24$ will be effective to detect impactors whose size is more than 50 m. However, more improvement in $J_1$ is necessary to detect Chelyabinsk-class impactors (i.e., 25 m).

4. NEO Orbit Determination

In this section, the orbit determination, O/D, of detected NEOs is conducted based on the results of the above-mentioned NEO detection simulation. “0.001”° angle error is applied to the NEO observation data for the simulation of O/D.

As mentioned previously, the angle-only observation data is used for O/D, and the frequency of the observation is once per day. In this case, the position error of the space telescope produces angle error in the observation data; hence, it should be evaluated first. Figure 20 shows the relationship between the position error of the space telescope and the angle error of NEO observation data.

As shown in Fig. 20, if the position error exceeds 1,000 km, the observation angle error produced by the position error exceeds the assumed angle error (i.e., 0.001°). However, the O/D error in the vicinity around the Sun-Earth L1 or L2 points is about 10 km in position error, hence, the position error of the telescope can be assumed to be negligible.

Figure 21 shows the results of the O/D analysis. “NEOs 1–3” in Fig. 21 are summarized in Table 9. In this analysis, the orbit is determined through a batch least squares method based on the observed angle-only data. The orange areas in Fig. 21 correspond to the observation data sets. The numbers of the areas indicate the number of observation, which equal the number of days. While data is not available, the covariance is simply propagated. The position error of the telescope is set to be 10 km and it is considered in the O/D as a “consider parameter” which describes the effect of unmodeled, systematics errors in the covariance computation. $\sigma_R$ “sigma-R” in Fig. 21 is the standard deviation of the estimated position error of the NEO.

As shown in Fig. 21, the O/D precision varies in NEOs 1–3. The authors speculate that the number of observations is the most sensitive factor for precision. A large number of observations gives us the state values of the orbit in long-arc, which will improve O/D precision.
The NEO position error in the worst case at 0.05 au from the Earth is about 1,000 km, which will be precisely enough to judge the possibility of Earth impact. However, this study evaluates O/D precision in only three cases; hence, further study will be necessary to evaluate the feasibility of the proposed mission concept.

5. Conclusion

This paper proposed the concept for a NEO detection and impact hazard warning system utilizing a space telescope placed at Sun-Earth Lagrange point-1, which intensively observes the NEOs in-coming from the noon-side that are hard to observe using ground-based telescopes. Two cases of NEO detection schemes were considered in this study: Case-1, in which the space telescope observes a concentrated region at far range from the Earth; and Case-2, in which the telescope observes half of the sky around the Sun at a short range from the Earth. The results of the NEO detection simulation revealed that Case-1 is superior to Case-2 when we consider small size of NEOs. This is because the distribution of NEOs becomes smaller at far slant range and it scatters when approaching the Earth. The integration time per field-of-view of the telescope becomes large when the observation region is narrow; hence, Case-1 can observe small NEOs at a far range (i.e., before the distribution of NEOs scatters). The position estimation precision at Earth impact was evaluated through orbit determination analysis based on angle-only observation data considering the position error of the space telescope. The position estimation error is about 1,000 km in the worst case, which will be precise enough to evaluate the possibility of Earth impact.

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Table 9. Major parameters of NEOs 1–3.

| Name | $a$ [au] | $e$ | $i$ [deg] | $V_1$ [km/s] | Number of observations |
|------|---------|-----|-----------|--------------|-----------------------|
| NEO1 | 1.03    | 0.50| 35.40     | 22.87        | 42                    |
| NEO2 | 0.77    | 0.37| 27.88     | 15.68        | 126                   |
| NEO3 | 0.90    | 0.26| 7.24      | 8.39         | 267                   |

Fig. 21. Position error of NEO orbit determination.