DESIGN CONSTRAINTS FOR ASTEROID DEFLECTION CAMPAIGNS BASED ON DELTA-V ESTIMATION TIMELINES

R. Makadia[1], D. Farnocchia[2], B.W. Barbee[3], S. Eggl[1], [1]University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA; [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA; [3]NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

Keywords: Kinetic Impactors, Asteroid Deflection, Orbit Determination

Introduction: Thanks to the success of NASA's DART mission, the Kinetic Impact (KI) method is now a demonstrated way of deflecting Near-Earth Asteroids (NEAs) away from the Earth [1]. One important caveat with KI deflections is the potential of unintentionally fragmenting the target when aiming to deflect it. An unintended fragmentation event is more likely to happen if the NEA is a small rubble pile or if the relative impact momentum of the KI spacecraft is too high. Recent studies indicate that fragmentation can be avoided if the change in velocity (ΔV) of the asteroid due to a KI mission is less than 10% of its surface escape velocity [2]. Previous studies have considered multiple, smaller deflections to avoid fragmenting the target [3] and to increase the momentum transfer efficiency for targets with high curvature [4]. Campaigns with multiple KI spacecraft also offer redundancy in case one spacecraft fails to hit the target.

In order to safely conclude whether the hazard from an impacting NEA has been mitigated (using one or more deflection spacecraft), we must estimate the ΔV as a consequence of the deflection. Doing so requires observations of the NEA both before and after the deflection event. The fastest method of acquiring these measurements is to have a rendezvous reconnaissance spacecraft that remains in close proximity to the target. In this scenario, spacecraft radiometric tracking data can constrain the position of the target asteroid, as was done using the OSIRIS-REx spacecraft at (101955) Bennu [5].

In this work, we provide timelines for estimating the ΔV for a deflection of the hypothetical asteroid 2024 PDC$_{25}$. We assume the presence of a reconnaissance spacecraft that can be tracked around the target NEA before and after each deflection. Using this tracking data, we look to place constraints on the minimum time required to estimate the ΔV after a deflection. This is especially important for campaigns with multiple deflections because the uncertainties in the target's position compound after each deflection. We apply this analysis to the hypothetical asteroid impact exercise based on asteroid 2024 PDC$_{25}$ and provide some generalized conclusions for any impacting asteroid.

Methods: This work starts with the information available for 2024 PDC$_{25}$ as of April 28, 2028 (Epoch 2 of the hypothetical scenario[1]). The 390 astrometric observations, including 2 from the flyby spacecraft, are processed using the batch least squares orbit filter in the GRSS library [6]. The resulting orbit solution is used to compute the B-plane uncertainties of the impacting encounter in 2041. The B-plane is used because it helps reduce the complex 3-dimensional geometry of the close encounter to a 2-dimensional plane. And more importantly, it is defined in a way that allows an analysis of the close approach before the gravity of the Earth introduces significant nonlinearities [7]. It is defined as the plane that is perpendicular to the incoming asymptote of the asteroid's hyperbolic trajectory with respect to the Earth, with the origin coinciding with the center of the Earth.

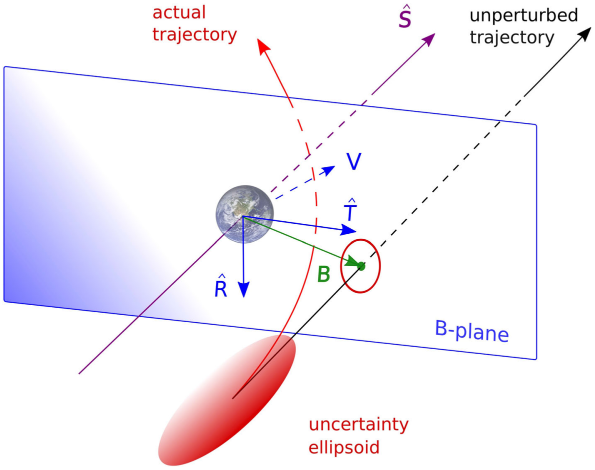

Figure 1: Graphical representation of the B-plane [7]. The nominal state of the approaching asteroid and its associated error ellipsoid are projected onto the B-plane as a point and an ellipse, respectively.

Figure 1 shows a graphical illustration of the B-plane. Since the nominal orbit crosses the B-plane at a single point, its uncertainties are represented as an ellipse. The dimensions of the major and minor axes of this ellipse are a direct function of the asteroid's orbital element uncertainties. Therefore, the B-plane uncertainty ellipse enables aster-

---

[1] `https://cneos.jpl.nasa.gov/pd/cs/pdc25/epoch2.html`

oid impact hazard assessment when we determine whether this ellipse intersects the Earth. Figure 2 shows the uncertainty evolution of the B-plane ellipse semi-major axis (SMA) and semi-minor axis (SMI) until April 2028.

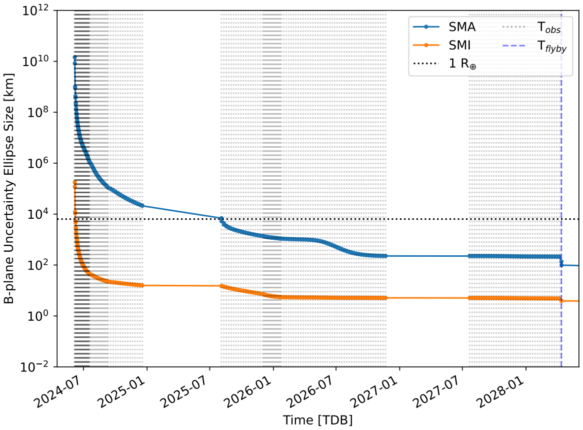

Figure 2: 2041 B-plane uncertainty evolution of 2024 PDC$_{25}$. The solid lines represent the 1σ dimensions of the B-plane ellipse. The blue vertical dashed line corresponds to the spacecraft flyby. The vertical dotted lines indicate the time of each observation before April 28, 2028 (Epoch 2).

The expected trends in the reduction of uncertainty are seen in Figure 2. Right after discovery in the first apparition, the uncertainty drops rapidly both as a function of the data arc length and the cadence at which the asteroid is observed. The second apparition further reduces these uncertainties since it increases the data arc to 2 years. The third apparition has a more modest effect until the flyby spacecraft provides 2 close-range optical navigation measurements. Since the flyby data are obtained from a significantly lower distance, they provide much tighter positional constraints than the ones obtained in the Earth plane-of-sky. As a result, they noticeably reduce the uncertainties on the 2041 B-plane.

In order to establish a timeline for estimating the ΔV vectors from multiple KI spacecraft, we must pick a time to begin deflecting the asteroid. We choose the perihelion pass of 2024 PDC$_{25}$ in December 2034 since this provides maximum efficiency (given that the asteroid is being deflected at/around perihelion) and allows ample time for both launching the KI spacecraft and getting the reconnaissance spacecraft in orbit around the target before the deflections. Furthermore, deflecting in 2034 also gives plenty of time until the hypothetical impact in 2041 to allow the resulting orbital displacement to accumulate over more than 6 years. As far as campaign design goes, Table 1 shows the design parameters for one representative multiple KI deflection campaign.

Table 1: Design parameters for a representative multiple KI deflection campaign

Parameter	Value
Number of KI spacecraft	3
Recon. spacecraft residence time	30 days
Pre-deflection ConOps time	1 day
Post-deflection ConOps time	7 days
Deflection interval (ΔV span)	15 days
Pseudo-range measurement span	7 days
Pseudo-optical measurement span	7 days

The number of KI spacecraft was chosen to be 3 because of both technical and implementation constraints. We need at least 2 KI spacecraft for a campaign in the case where a single large KI might fragment the target. However, in a realistic multiple-KI campaign, we would want to have a third spacecraft as a backup in case one of the primary KI spacecraft fails to hit the target. Furthermore, having 3 KI spacecraft lets us assess any differences in the ΔV estimates between deflections 1&2 and deflections 2&3. The reconnaissance spacecraft residence time is the amount of time used for tracking the target before the first deflection and after the last deflection for the sole purpose of improving the target asteroid ephemeris for aiding in ΔV estimation.

The Concept of Operations (ConOps) time is the time taken to ensure spacecraft safety and readiness before and after each deflection. Before the deflection, the spacecraft is able to stay until a day before the event. At this point, the spacecraft would have to start moving away from the target to protect itself from the ejecta debris kicked off the target asteroid during deflection. After the deflection, the spacecraft can return to the target after a week. This allows enough time for the ejecta to clear out and for the spacecraft to return to the target from its observing posture. The deflection interval is the time between each deflection. As a result, it is also the time available to estimate the ΔV from the previous deflection before the next one using the tracking measurements of the reconnaissance spacecraft.

Two types of spacecraft tracking measurements are considered in this work: pseudo-range measurements from spacecraft ranging data and pseudo-optical measurements from spacecraft ΔDOR data. The basic procedure for acquiring both types of pseudo-measurements is to combine Earth- and asteroid-relative measurements of the reconnaissance spacecraft when it is orbiting the target asteroid. The Doppler tracking and optical navigation data for the spacecraft constrain its state with respect to the asteroid. The ranging and ΔDOR data independently constrain the state of the spacecraft with respect to the ground stations on the Earth. Combined, they can yield pseudo-range and pseudo-optical measurements that can help constrain the asteroid's geocentric state.

The pseudo-range measurements can be used to obtain a geocentric delay measurement of the target asteroid. This has already been done by the OSIRIS-REx spacecraft at Bennu [5], and it led to an unprecedented level of fidelity in Bennu's orbit solution. The minimum time span for each pseudo-range measurement in that work was 7 days, which is also the value we adopt in this work.

The second type of tracking data needed is Delta-Differential One-Way Range (ΔDOR). This is a technique used in radio science and navigation to measure the spacecraft's angular position. The ΔDOR measurements apply very long baseline interferometry techniques to spacecraft radiometric tracking [8]. The basic idea is that two radio stations on the Earth simultaneously conduct ranging measurements to the spacecraft. The difference in the time of arrival of the signal at the two stations is used to estimate the angular position of the spacecraft [9]. Today, these ΔDOR measurements can provide angular accuracies as low as 1 nanoradian [8]. We assume that 7 days of tracking data can also be used to obtain pseudo-optical astrometry from ΔDOR measurements. These measurements are extremely valuable since they constrain the target in the plane-of-sky, which perfectly complements the pseudo-range measurements. Together, these two types of measurements constrain the asteroid's position in all three dimensions. Additionally, we conservatively assume that these pseudo-optical ΔDOR measurements have an uncertainty of 2km at 2au, which is the approximate geocentric distance of 2024 PDC_{25} during the 2034 perihelion pass. This leads to an angular measurement uncertainty of 6.7 nanoradians or 1.4 milliarcseconds, which is a conservatively high value (6.7x higher) compared to the traditional spacecraft ΔDOR measurements.

Results: Once we have the measurement schedule and the multiple KI deflection campaign designed, we can compute the ΔV estimates after each deflection. We achieve this by adding synthetic measurements (pseudo-range and pseudo-optical) to the observation data for 2024 PDC_{25} and then estimating the orbital and dynamical parameters for the asteroid. The resulting orbit solution is used to compute the B-plane uncertainties during the 2041 encounter after each measurement. It is these uncertainties on the B-plane that dictate whether we can conclusively say that the asteroid has been deflected enough to avoid an impact with the Earth. We start by assessing the ΔV estimation timelines for an observation schedule without and with the pseudo-optical measurements. Then, we perform a sweep over the deflection interval to assess its effect on the ΔV estimation timeline.

Figure 3 shows the B-plane uncertainty evolution of 2024 PDC_{25} during a multiple KI deflection campaign without any optical astrometry from pseudo-optical measurements. As expected, the B-plane uncertainties grow significantly after each deflection. However, one thing to note in this case is that, over the course of the deflection campaign, the semi-major axis of the B-plane uncertainty ellipse is never less than 1 Earth radius. It is not until 3 weeks after the last deflection that the B-plane semi-major axis drops below 1 Earth radius.

On the other hand, Figure 4 shows the B-plane uncertainty evolution of 2024 PDC_{25} during a multiple KI deflection campaign with pseudo-optical astrometry from ΔDOR measurements. The uncertainties are significantly lower after the inclusion of the pseudo-optical measurements. As mentioned before, this is because they help provide information about the asteroid's coordinates in all three position dimensions when combined with pseudo-range measurements.

This is further evidenced by the results shown in Figure 5. This figure shows the position uncertainties for 2024 PDC_{25} at different key times in the deflection campaigns. The deflection interval is varied from 15 to 70 days. The solid lines indicate an observation schedule with pseudo-optical measurements, while the dashed lines indicate an observation schedule without them. The top row shows the uncertainty ellipse evolution on the B-plane (with a horizontal dotted line showing 1 Earth radius), while the bottom row shows the position uncertainty ellipsoid evolution in the Right Ascension (RA), Declination (Dec), and Range (Rng) orthonormal basis.

The positive effects of the pseudo-optical measurements are clear even before the first KI space-

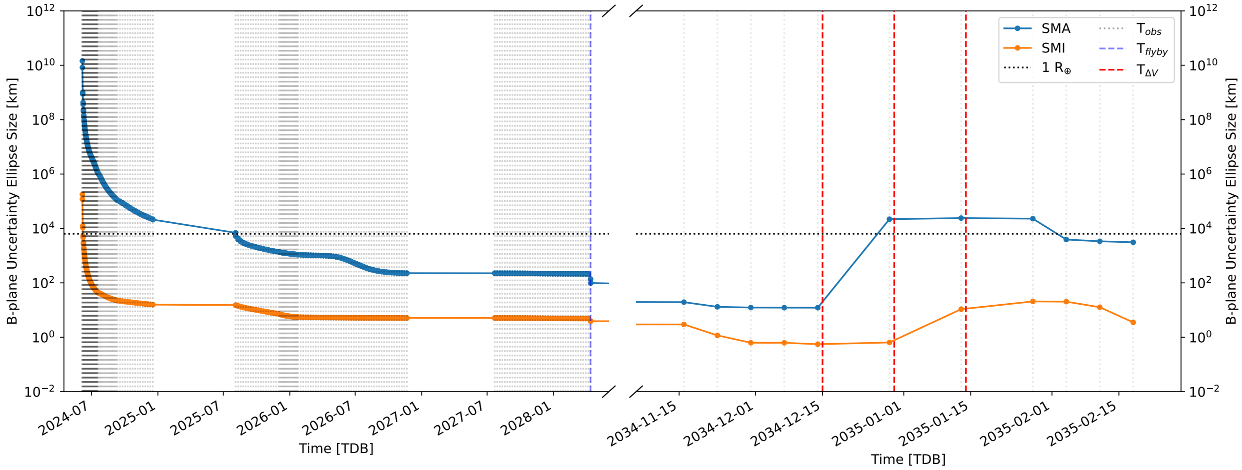

Figure 3: 2041 B-plane uncertainty evolution of 2024 PDC$_{25}$ during a multiple KI deflection campaign without any derived astrometry from pseudo-optical measurements. The solid lines represent the 1σ dimensions of the B-plane ellipse. The vertical dotted lines indicate the time of each observation. The blue vertical dashed line corresponds to the spacecraft flyby. The red vertical dashed lines indicate the time of each deflection. The horizontal dotted lines correspond to 1 Earth radius.

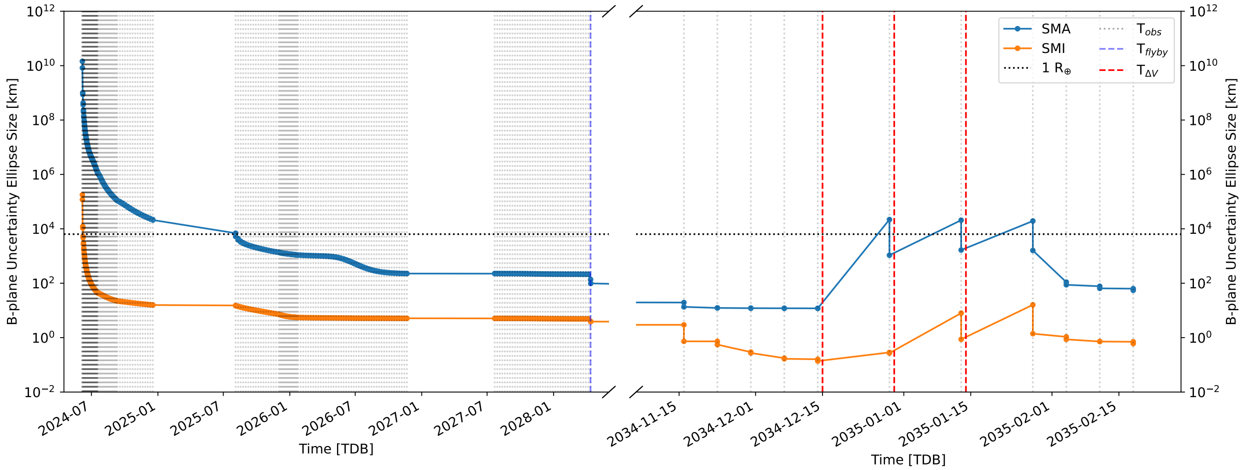

Figure 4: 2041 B-plane uncertainty evolution of 2024 PDC$_{25}$ during a multiple KI deflection campaign with derived astrometry from pseudo-optical measurements. The solid lines represent the 1σ dimensions of the B-plane ellipse. The vertical dotted lines indicate the time of each observation. The blue vertical dashed line corresponds to the spacecraft flyby. The red vertical dashed lines indicate the time of each deflection. The horizontal dotted lines correspond to 1 Earth radius.

craft hits the target. Since these are angular measurements in the plane-of-sky, they do not provide significant improvement in the range uncertainties. However, they do provide better angular uncertainties by nearly an order of magnitude before the first deflection. Between the three deflections, the pseudo-optical measurements provide 1 order of magnitude improvements in the B-plane uncertainties, which are ultimately what drive the decision-making process for concluding whether the asteroid has been deflected enough to avoid an impact with the Earth. Most importantly, these effects are especially higher for lower values of the deflection interval. This further demonstrates that obtaining these pseudo-optical measurements not only improves overall prediction uncertainties, but also enables shorter deflection intervals.

Conclusions: The work done in this extended abstract shines a light on the timelines associated with asteroid deflection campaigns that use multiple kinetic impactor spacecraft. A multiple-KI campaign might be necessary for small asteroids to ensure deflection instead of unintended fragmentation. In such a scenario, it is important to know how much time is needed between each KI deflection in order to estimate the results of the previous one.

Results show that at best, the minimum time between deflections in a multiple KI campaign for 2024 PDC_{25} needs to be around 2 weeks to achieve a B-plane uncertainty of 1 Earth radius before the next. This is only possible in the presence of pseudo-optical measurements from ΔDOR data, which require the presence of a reconnaissance spacecraft at the target asteroid. Without them, the minimum time is around 3-4 weeks. Adhering to this minimum deflection interval constraint would enable informed decision-making between each deflection and allow us to assess whether the asteroid has been sufficiently deflected during the campaign. Without the presence of an observer spacecraft, and sufficient KI intervals, our ability to reassess the asteroid's impact hazard between deflections would be significantly reduced. In such a scenario, the campaign would have to follow a preset strategy without the ability to update it after each deflection. We would only be able to conclude whether the impact hazard from the NEA has been mitigated after all the deflections were complete, and we would have incomplete knowledge of the ΔV vectors at each deflection.

These minimum deflection interval constraints are also applicable to other asteroids since the primary driver of the ΔV estimation timeline is the number and quality of tracking measurements available for the target asteroid. The 2041 B-plane uncertainty evolution for 2024 PDC_{25} does not show any secular trends resulting from the dynamics of the target asteroid. This means that the results presented here can be used to provide a first-order value of 2-3 weeks for the minimum deflection interval that allows for interim decision-making in a multiple-KI campaign.

References: [1] N. L. Chabot, et al. (2024) *The Planetary Science Journal* 5(2):49 `doi`. [2] K. M. Kumamoto, et al. (2024) in *2024 American Geophysical Union Annual Meeting*. [3] National Research Council (2010) *Defending Planet Earth: Near-Earth-Object Surveys and Hazard Mitigation Strategies* National Academies Press ISBN 9780309157216. [4] M. Hirabayashi, et al. (2025) *Nature Communications* 16(1):1602 `doi`. [5] D. Farnocchia, et al. (2021) *Icarus* 369:114594 `doi`. [6] R. Makadia, et al. (2025) *The Planetary Science Journal* 6 `doi`. [7] D. Farnocchia, et al. (2019) *Celestial Mechanics and Dynamical Astronomy* 131(8) `doi`. [8] D. W. Curkendall, et al. (2013) *Interplanetary Network Progress Report* 42-193:1. [9] T. H. Taylor, et al. (1984) *Journal of Guidance, Control, and Dynamics* 7(3):301 `doi`.

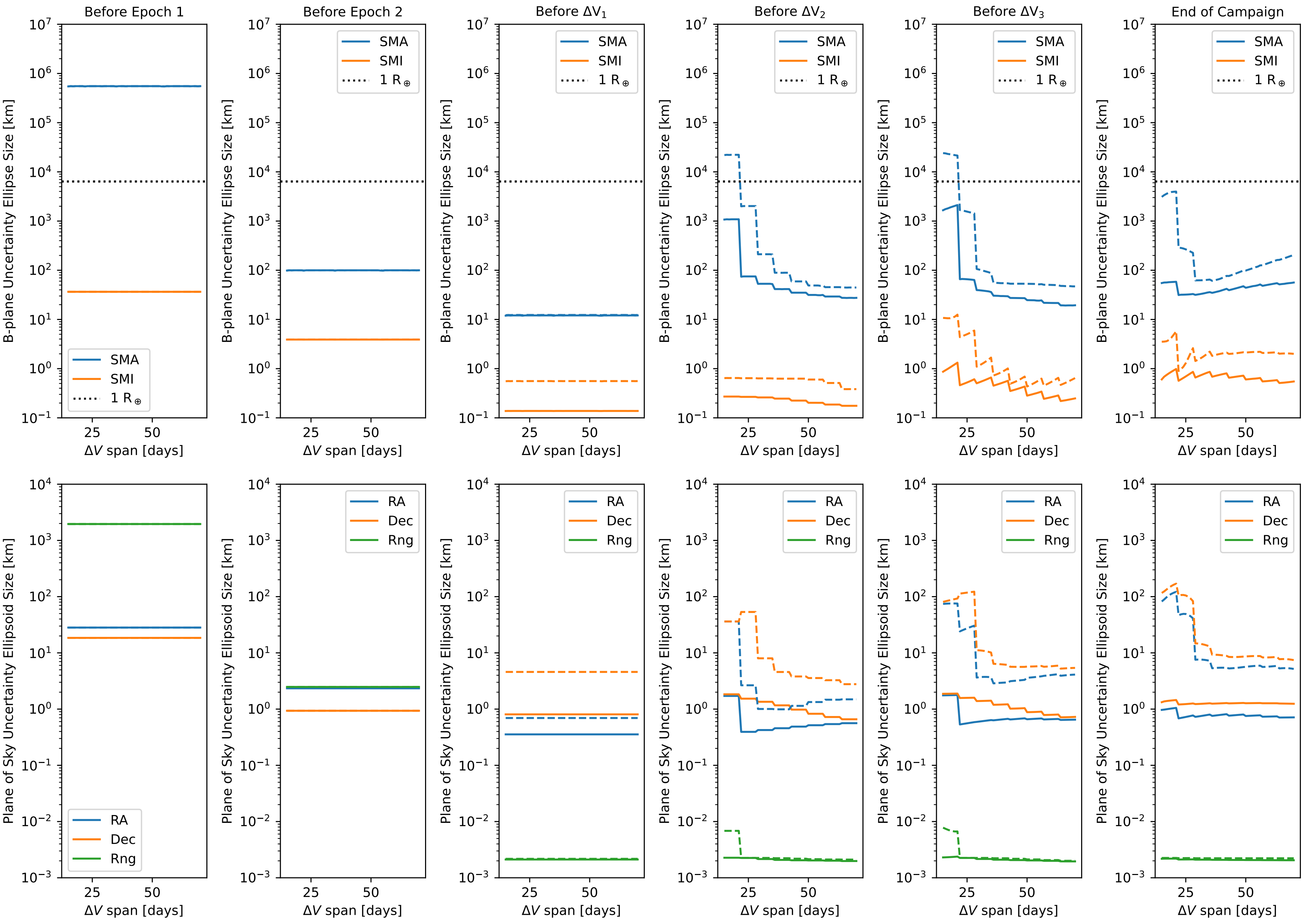

Figure 5: Position uncertainty evolution of 2024 PDC$_{25}$ at different key times in the deflection campaign. The deflection interval is swept from 15 to 70 days. Each column is titled with each key time in the deflection campaign. The solid lines indicate an observation schedule with both pseudo-range and pseudo-optical measurements, while the dashed lines indicate an observation schedule that only uses pseudo-range measurements. The top row shows the uncertainty ellipse evolution on the 2041 B-plane and the bottom shows the position uncertainty ellipsoid evolution in the plane-of-sky.