The Gaia-FUN-SSO observation campaign of 99942 Apophis: A preliminary test for the network

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1 Abstract

In order to test the coordination and evaluate the overall performance of the Gaia-FUN-SSO, an observation campaign on the Potentially Hazardous Asteroid (99 942) Apophis was conducted from 12/21/2012 to 5/2/2013 providing 2732 high quality astrometric observations. We show that a consistent reduction of astrometric campaigns with reliable stellar catalogs substantially improves the quality of astrometric results. We present evidence that the new data will help to reduce the orbit uncertainty of Apophis during its close approach in 2029.

2 Introduction

In the framework of the Gaia mission, an alert mode (a ground-based follow-up network [Thuillot, 2011]), has been set up in order to identify newly detected objects and trigger complementary observations from the ground, since the satellite cannot keep monitoring its discoveries. Specific training campaigns have been organized during the past three years. In particular, the observation campaign of Apophis from 12/21/2012 to 5/2/2013, providing 2732 valuable astrometric measurements among the collection of extensive observations. Some of the observations performed, already submitted to the MPC, have been reduced by the observers themselves, using their preferred tools and astrometric catalogs. However, we decided to conduct a complementary homogeneous reduction, with all CCD images recorded during this campaign using the PRAIA reduction pipeline [Assafin et al., 2011] and the UCAC4 astrometric catalog [Zacharias et al., 2013]. This yields to consistent set of 2732 astrometric measurements of Apophis. In the following we will discuss data analysis of the observations acquired by the Gaia-FUN-SSO. We will show that a consistent analysis can decrease systematic errors and boost the quality of astrometric positions.

3 Data analysis

Among the 2732 astrometric measurements, 629 had already been sent to the MPC by the observers. This gives us an unique opportunity to compare the consistency of these observations according to the catalog used for the data reduction. We thus define:

- $D_{\text{MPC}}$ as the 629 duplicated Gaia-FUN-SSO astrometric measurements already sent to the MPC by the observers. The corresponding observations were reduced with various astrometric software packages and catalogs.
- $D_{\text{PRAIA}}$ as the same 629 Gaia-FUN-SSO observations, but re-reduced with PRAIA using the UCAC4 astrometric catalog.
- $S_{\text{NEW}}$ as the 2109 unsent observations.
3.1 Alert and recovery process

Using a similar approach as Bancelin et al. [2012], we aim to assess how far the predicted position can drift from the real one in a given amount of time. Let us consider a hypothetical discovery of an asteroid during the Gaia-FUN-SSO campaign. We will use the observational data of Apophis, but we shall assume its orbit was previously unknown. Furthermore, we assume that the hypothetical discovery has happened on the first night recorded in the duplicated measurements $D_{PRAIA}$ and $D_{MPC}$. This first night set is used to determine the orbit and orbital elements covariance matrix of the new object. We then propagated the orbit solutions and uncertainties obtained from both sets up to six days after the discovery. One week after the discovery the coordinate differences $\Delta \alpha$ and $\Delta \delta$ between $D_{PRAIA}$, $D_{MPC}$ and the "true" position of Apophis (obtained with the 2004-2014 optical and radar data) are evaluated. Figure 1 shows how the differences in astrometric coordinates evolve for both sets of measurements during the six days following the discovery. The opposing orientation of the $(\Delta \alpha, \Delta \delta)_{MPC}$ and $(\Delta \alpha, \Delta \delta)_{PRAIA}$ curves is due to the different preliminary orbital elements found using $D_{PRAIA}$ and $D_{MPC}$. One can see that $(\Delta \alpha, \Delta \delta)_{MPC}$ and $(\Delta \alpha, \Delta \delta)_{PRAIA}$ are of the same order of magnitude. Consequently, the method of data reduction is unlikely to have a significant impact on the recovery process within the network.

![Figure 1](image1.png)

**Fig. 1** – The graph shows the time evolution of the coordinate differences $(\Delta \alpha, \Delta \delta)_{MPC}$ and $(\Delta \alpha, \Delta \delta)_{PRAIA}$ between orbit solutions derived from different data sets with respect to the nominal solution (obtained using all the optical and radar data available).

3.2 Position uncertainty propagation for new discoveries

We are now interested in how the position uncertainty evolves when more observations become available during the nights following an asteroid’s discovery. As we assume the asteroid to be newly discovered, a preliminary orbit determination is conducted after the first night of the sets $D_{PRAIA}$ and $D_{MPC}$ and an orbital improvement is performed. Uncertainties on the geocentric position is then calculated. This allows us to compare the impact of the reduction pipeline on the uncertainty evolution of a newly found object. Figure 2 shows that at the discovery night (first night), uncertainties are large for both sets. However, it is only after the 10th night that the difference $D_{MPC} - D_{PRAIA}$ drops permanently below 10 km. Since between the first and the 10th night span an arc of 26 days, there is a real advantage in consistent reduction regarding the position uncertainty propagation of follow up campaigns.
3.3 Orbit propagation for Apophis

We will now proceed to study whether orbits and initial uncertainties constructed from different sets of observations can cause a significant change in the propagated uncertainties of Apophis’ orbit. The process then works as follows. After an initial orbit determination, an orbit adjustment based on a differential correction is performed. This results in the uncertainties of the asteroids orbit in form of an orbital element covariance matrix. The resulting uncertainties can then be propagated to the 2029 b-plane and its long axis was used to indicate the 1σ uncertainty value. A quick first check can be performed using the duplicated measurement sets \( \text{DMPC} \) and \( \text{DPRAIA} \). The propagated uncertainty with \( \text{DPRAIA} \) improves the 1σ uncertainty obtained with \( \text{DMPC} \) by \( \sim 14\% \) which is non negligible for the impact probability assessment with short arc data.

3.4 Impact of Gaia-FUN-SSO Observations on Orbit Uncertainties

Our aim is to investigate whether the consistent data produced during the Gaia-FUN-SSO campaign can impact orbital solutions and b-plane uncertainties through the example of Apophis. To this end we compare orbits and uncertainties derived from five observational data sets:

- \( S_1 = [2004-2014]_{\text{MPC}} + \text{radar} \)
- \( S_2 = [2004-2014]_{\text{MPC}} - \text{DMPC} + \text{DPRAIA} + \text{radar} \)
- \( S_3 = S_1 + S_{\text{NEW}} \)
- \( S_4 = S_2 + S_{\text{NEW}} \)
- \( S_5 = S_{\text{NEW}} + \text{DPRAIA} + \text{radar} \)

where \([2004-2014]_{\text{MPC}}\) refers to the 4138 optical data as present in the MPC database. We propagated each nominal orbit resulting from the individual sets of observations together with its covariances up to 2029 where we evaluated the position uncertainties projected onto the b-plane. Table 1 summarizes the quality of the orbital fit and the 2029 b-plane uncertainty resulting from the orbit propagation. The presented results suggests the sets containing \( \text{DPRAIA} \) instead of \( \text{DMPC} \) result in smaller uncertainties in Apophis’ positions in the 2029 b-plane. Indeed, even for a well-known orbit (with a 10-years arc data length), both optical and radar \( \chi^2 \) values show better results when \( \text{DPRAIA} \) measurements are used. Hence, we speculate that current orbit solutions of NEAs can be improved using consistent data. Furthermore, consistent data reduction with a good astrometric catalog can also result in smaller uncertainties in the b-plane.


Tab. 1 – Orbital accuracy information – fit residuals and b-plane uncertainty – computed with different sets of observations. We also computed the difference in b-plane distance $\Delta_i$ for each set with respect to the distance $\Delta_1$ obtained from $S_1$.

| $S$ | $\chi^2_{\text{opt}}$ | $\chi^2_{\text{rad}}$ | $\sigma_\zeta$ [km] | $\Delta_i - \Delta_1$ [km] |
|-----|----------------------|----------------------|----------------------|----------------------|
| $S_1$ | 0.227               | 0.434               | 2.99                 | 0                    |
| $S_2$ | 0.224               | 0.426               | 2.94                 | 0                    |
| $S_3$ | 0.157               | 0.175               | 2.45                 | 1.5                  |
| $S_4$ | 0.155               | 0.174               | 2.43                 | 1.5                  |
| $S_5$ | 0.021               | 0.095               | 3.24                 | 3                    |

coordinates of PHAs, as was shown for the 2029-b-plane of Apophis. Moreover, we see that the Gaia-FUN-SSO observations and radar data ($S_5$) suffice to produce b-plane uncertainty values that are very close to those sets that contain all available observations.

4 Conclusion

A large amount of astrometric data was collected during the latest period of observability of Apophis in 2012-2013 and processed in a homogeneous fashion using the PRAIA reduction software and the UCAC4 catalog data. Using the 629 duplicated data from the 2732 precise astrometric measurements provided by 19 observatories, we could show that the recovery process of new objects when their observational data arcs span less than one night won’t be impact when considering MPC or PRAIA data. However, a consistent data reduction of a newly discovered asteroids during this observation campaign would have led to a greater reduction of NEO position uncertainties. Finally, the example of Apophis reveals that, even for well-known orbits, the use of consistent data can improve the current $\chi^2$ of both optical and radar data.

Références

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