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Look Up (Again) The Apophis Asteroid: Simulating and Visualizing Orbit

Cahyo Puji Asmoro[1]*, Judhistira Aria Utama[2], Deni Karsa Sondana[3]

[1] *Astronomy Postgraduate Program, Institut Teknologi Bandung, Indonesia, 20322005@mahasiswa.itb.ac.id*
[2] *Physics Study Program, Universitas Pendidikan Indonesia, Indonesia, j.aria.utama@upi.edu*
[3] *Physics Postgraduate Program, Institut Teknologi Bandung, Indonesia, 24721004@mahasiswa.itb.ac.id*

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ABSTRACT

The asteroid Apophis, first discovered in 2004 by American astronomers, is known to have a dangerous potential for planet Earth. Many early studies predict that in 2029 it will experience a close encounter and have a possible collision with the Earth at the next close encounter due to keyhole gravity. This research will explain how to carry out an orbit simulation using an orbit integrator to review this possibility and the evolution of the Apophis asteroid orbit over the next 500 years. The results of this study are expected to provide an understanding of simulating asteroid orbit from its orbital parameters and to build awareness of the threat of danger from small solar system objects such as asteroids, comets, and meteoroids.

Keywords: Apophis, Ephemeris, Planetary defense system

ABSTRAK

Asteroid Apophis yang ditemukan pada tahun 2004 oleh astronom Amerika, dikenal memiliki potensi berbahaya bagi planet Bumi. Banyak penelitian awal yang memperkirakan bahwa pada tahun 2029 asteroid ini akan mengalami papasan dekat dengan Bumi dan berkemungkinan mengalami tabrakan pada papasan dekat berikutnya akibat *keyhole gravity*. Penelitian ini akan memaparkan bagaimana melakukan simulasi orbit asteroid menggunakan integrator orbit untuk meninjau kembali kemungkinan tersebut dan bagaimana evolusi orbit asteroid Apophis selama 500 tahun ke masa depan. Hasil dari penelitian ini diharapkan mampu memberikan pemahaman tentang cara melakukan simulasi orbit asteroid dari parameter orbitnya, sekaligus sebagai upaya membangun kewaspadaan terhadap ancaman bahaya luar angkasa dari benda kecil tata surya seperti asteroid, komet, maupun meteoroid.

Kata kunci: Apophis, Efemeris, Sistem pertahanan planet

INTRODUCTION

At the end of 2021, a movie entitled "Don't Look Up" caught the attention of science fiction movie lovers. The film talks about Kate Dibiasky (Jennifer Lawrence), an astronomy graduate student, and her professor Dr. Randall Mindy (Leonardo DiCaprio), making a surprising discovery about a comet orbiting within the solar system. The problem is - it's on a direct collision course with the Earth. Another problem is that no one seems to care. It turns out that warning humanity about a planet-killer the size of Mount Everest is a detailed fact to convey and resolve. There are many diverse views on this event, be it concerns for the survival of living things, distrust of scientific predictions, and some even see it as a business opportunity. So the film's title, "Don't Look Up," is an expression for those who don't believe or don't care about the fact that comets exist (Little, 2022).

Comets and other small objects in our solar system, such as asteroids and meteoroids, have destructive potential. The existence of asteroids in our solar system is one thing that cannot be denied, and it is even believed that asteroids bombarded our Earth at one time. This bombardment was also experienced by other massive objects in the solar system, such as the planet Mercury and our satellite, namely the Moon, whose surface we can still see many signs of collisions from Asteroids (Lang, 2011). Observations show that asteroids are divided into several populations, most of which are in the main belt between Mars and Jupiter, the Kuiper belt across from Neptune, and the area around Earth (Riza et al., 2022).

There is another population of asteroids known as Near-Earth asteroids (NEAs). This population is conventionally defined as small bodies with a perihelion distance of less than or equal to 1.3 au (Astronomical Unit; 1 au equals 149,597,870.7 km). Compared to the main belt asteroids (MBAs), NEAs tend to be smaller and irregularly shaped with short dynamic life spans. NEAs with a minimum orbital intersection distance (MOID) to the Earth's orbit of less than 0.05 au and an absolute magnitude H less than or equal to 22 (approximately 140 m in diameter) are officially classified as Potentially Hazardous Asteroids (PHAs). This naming is not to ensure that there will be a collision with the objects in question but to indicate that they can cause massive damage upon collision with Earth (Satpathy et al., 2022; Vernazza et al., 2021).

NASA provides information about PHAs at the site at cneos.jpl.nasa.gov/sentry/, as well as at newton.drn.unipi.it/neodys2/ (Thiry & Vasile, 2016). The PHAs can experience a deep close encounter with the Earth or even crashes directly. Based on existing records on the Earth, a collision with an asteroid of 100 meters in diameter can cause local damage, for example, the Tunguska event caused by a 60 meters asteroid (Davydov, 2021). The other case is the Chelyabinsk event which is associated with a 17 meters asteroid (Mashkova et al., 2019). Asteroids up to one kilometer in diameter can cause an associated regional catastrophe. Earth faces a global catastrophe when the size of the asteroid is larger than one kilometer (Sokolov et al., 2019).

Modern observation tools made it possible to detect and investigate dangerous asteroids, and the development of space awareness systems made it possible to solve the problem of preventing an asteroid collision with the Earth. In early October 2022, international cooperation between NASA and ESA succeeded in carrying out a test mission to change the asteroid's orbit. NASA, in this case, the Planetary Defense Coordination Office (Andrews et al., 2021), plays a role in developing the Double Asteroid Redirection Test (DART) mission which crashes satellites into asteroids known as kinetic impactors. At the same time, ESA carries out the Asteroid Impact and Deflection Assessment (AIDA) mission, which will be a follow-up mission to characterize targets and measure deflection results (Cheng et al., 2018; Paris, 2020).

In the case of amateur astronomers, they can perform calculations and re-analyze the orbit of an asteroid or comet to inspect whether or not a close encounter or even a collision is possible. Furthermore, we can understand in depth whether these small objects are dangerous or not from their ephemeris that can be obtained from observations (Chichura et al., 2022). This article will explain step-by-step how to determine the orbit of an asteroid and the potential danger it has, with the object as the case is asteroid Apophis. Apophis is an interesting asteroid because its initial collision probability is estimated to be as high as 2.7% for the year 2029. It is expected to enter what is known as a gravity keyhole, which could exacerbate the probability of an impact in 2036 (Sokolov et al., 2021; Fauziah et al., 2020; Utama & Rusdiana, 2020).

METHODOLOGY

The materials/tools used in this research are as follows:
1. Asteroid ephemeris data
2. Laptop
3. The Solevorb.exe program
4. Orbe.exe program
5. Colosionlab.exe program
6. Grafica.exe program
7. Evolucion.exe program
8. Vis2orbit.exe program

Our research method is experimental (Taşcan & Ünal, 2021), by reconstructing the orbit of the asteroid Apophis based on ephemeris data (available from https://ssd.jpl.nasa.gov/tools/sbdb_lookup.html#/?sstr=apophis&view=VOPCRA). We employed the Solevorb program to integrate the asteroid's orbit for the next 500 years to determine the possibility of the asteroid experiencing a close encounter or collision with the Earth. We also employed the Orbe program to check the consistency of the calculated orbit. After that, we performed close encounter distribution analysis and created an orbit evolution animation using the Colisionlab program. The three selected programs above are based on the Windows operating system and can be freely downloaded at http://www.fisica.edu.uy/~gallardo/#Program.

RESULTS AND DISCUSSION

Every solar system object has a parameter representing its position and motion (Mulyani et al., 2020). Like planets that interact gravitationally with the sun, so does the asteroid. Furthermore, small objects, such as asteroids, are also influenced by gravitational attraction from massive bodies. For orbit integration, we need to provide the orbital elements of the planet besides the asteroid itself. The six orbital parameters consist of semimajor axis (a), eccentricity (e), inclination (i), longitude of ascending node (Ω), argument of perihelion (ω), and mean anomaly (M) as shown in Figure 1 (Greenberg, 1982).

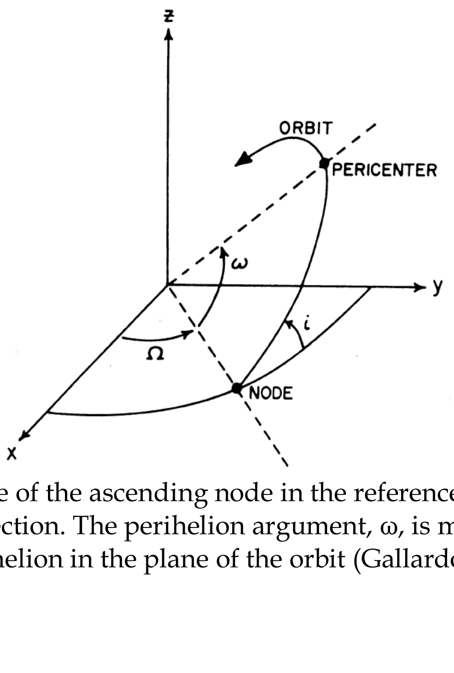


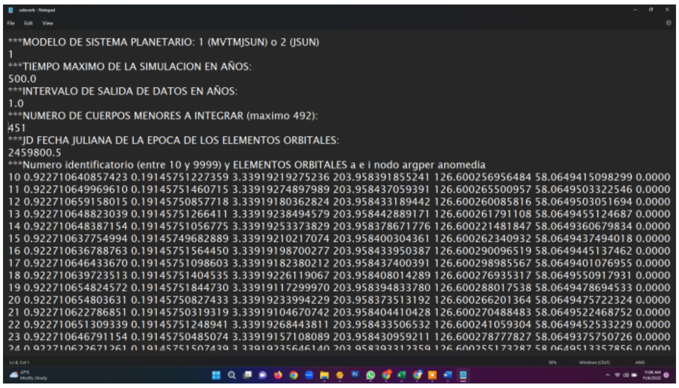
Figure 1. Ω is the longitude of the ascending node in the reference plane, xy, measured from the x reference direction. The perihelion argument, ω, is measured from node to perihelion in the plane of the orbit (Gallardo, 2019).

The asteroid Apophis's orbital parameter (OP) comes from the Small-Body Database Lookup site for a particular epoch (the time when the orbital parameter is calculated), as tabulated in Table 1. We also cloned up to 1000 asteroids as virtual objects of the nominal asteroid (Apophis) with variations within 5σ (5 times the nominal orbital uncertainty value of Apophis). Due to program limitations according to the number of objects being calculated, then we first divide 1001 objects into three calculation batches, namely batch-1 (consisting of 451 asteroids), batch-2 (consisting of 451 asteroids), and batch-3 (consisting of 99 asteroids, including the nominal asteroid Apophis).

Table 1. Parameters orbit of the asteroid apophis

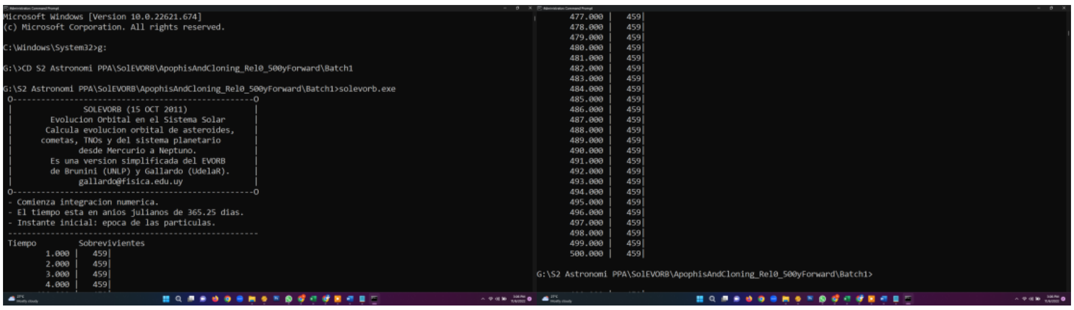
OP	a	e	i	ω	Ω	M
Value	0.922710	0.191457	3.339191	126.60026	203.95842	58.064946
Sigma	2.28E-09	1.21E-09	1.10E-07	4.09E-06	3.78E-06	7.72E-07

Before we employ the Solevorb program to integrate the orbit, we need to prepare some parameters (model of the solar system, computation duration, time step, etc.) as input for the program, saved by default in the file solevorb.ent (see Figure 2). Then we run the integrator from the Windows Command Prompt. The screenshots of the running program and final computation are shown in Figure 3. At the end of the computational process, the program gives some output files, namely (1) orbits (contains orbital elements *a*, *i*, *e*, *Ω*, *ω*, and *M* for each object), (2) xyzv (positions in x,y,z axis and corresponding velocity vx,vy,vz, (3) encuent (close encounter data among asteroids and planets), (4) colisio (collision event data), and (5) finales (contains data on close encounter and object ejection event). Some of the close encounter events with the Earth experienced by asteroid Apophis is presented in Table 2. The t enc is the time in years from the starting point of calculation (initial epoch) so that t1 enc = 6.682, which is the year 2029 for the close encounter to occur, t2 enc = 66.6795, which is the year 2089, t3 enc = 44.6789, which is the year 2067, and t4 enc = 81.6781, which is the year 2104.



```
***MODELO DE SISTEMA PLANETARIO: 1 (MVTMJSUN) o 2 (JSUN)
1
***TIEMPO MAXIMO DE LA SIMULACION EN AÑOS:
500.0
***INTERVALO DE SALIDA DE DATOS EN AÑOS:
1.0
***NUMERO DE CUERPOS MENORES A INTEGRAR (maximo 492):
451
***JD FECHA JULIANA DE LA EPOCA DE LOS ELEMENTOS ORBITALES:
2459800.5
***Numero identificatorio (entre 10 y 9999) y ELEMENTOS ORBITALES a e i nodo argper anomedia
10 0.922710640857423 0.19145751227359 3.33919219275236 203.958391855241 126.600256956484 58.0649415098299 0.0000
11 0.922710649969610 0.19145751460715 3.33919274897989 203.958437059391 126.600265500957 58.0649503322546 0.0000
12 0.922710659158015 0.19145750857718 3.33919180362824 203.958433189442 126.600260085816 58.0649503051694 0.0000
13 0.922710648823039 0.19145751266411 3.33919238494579 203.958442889171 126.600261791108 58.0649455124687 0.0000
14 0.922710648387154 0.19145751056775 3.33919253373829 203.958378671776 126.600221481847 58.0649360679834 0.0000
15 0.922710637754994 0.19145749682889 3.33919210217074 203.958400304361 126.600262340932 58.0649437494018 0.0000
16 0.922710636788763 0.19145751564450 3.33919198700277 203.958433950387 126.600290096519 58.0649445137462 0.0000
17 0.922710646433670 0.19145751098603 3.33919182380212 203.958437400391 126.600298985567 58.0649401076955 0.0000
18 0.922710639723513 0.19145751404535 3.33919226119067 203.958408014289 126.600276935317 58.0649550917931 0.0000
19 0.922710654824572 0.19145751844730 3.33919117299970 203.958394833780 126.600288017538 58.0649478694533 0.0000
20 0.922710654803631 0.19145750827433 3.33919233994229 203.958373513192 126.600266201364 58.0649475722324 0.0000
21 0.922710622786851 0.19145750319319 3.33919104670742 203.958404410428 126.600270488483 58.0649522468752 0.0000
22 0.922710651309339 0.19145751248941 3.33919268443811 203.958433506532 126.600241059304 58.0649452533229 0.0000
23 0.922710646791154 0.19145750485074 3.33919157108089 203.958430959211 126.600278777827 58.0649375750726 0.0000
```

Figure 2. The screenshot of solevorb.ent file



```
Microsoft Windows [Version 10.0.22621.674]
(c) Microsoft Corporation. All rights reserved.

C:\Windows\System32>g:

G:\>CD S2 Astronomi PPA\SolEVORB\ApophisAndCloning_Rel0_500yForward\Batch1

G:\S2 Astronomi PPA\SolEVORB\ApophisAndCloning_Rel0_500yForward\Batch1>solevorb.exe
 O-----------------------------------------------O
 |            SOLEVORB (15 OCT 2011)             |
 |      Evolucion Orbital en el Sistema Solar    |
 |     Calcula evolucion orbital de asteroides,  |
 |     cometas, TNOs y del sistema planetario    |
 |            desde Mercurio a Neptuno.          |
 |       Es una version simplificada del EVORB   |
 |       de Brunini (UNLP) y Gallardo (UdelaR).  |
 |            gallardo@fisica.edu.uy             |
 O-----------------------------------------------O
 - Comienza integracion numerica.
 - El tiempo esta en anios julianos de 365.25 dias.
 - Instante inicial: epoca de las particulas.
 -------------------------------------------------
 Tiempo        Sobrevivientes
       1.000 |    459|
       2.000 |    459|
       3.000 |    459|
       4.000 |    459|
```

```
     477.000 |    459|
     478.000 |    459|
     479.000 |    459|
     480.000 |    459|
     481.000 |    459|
     482.000 |    459|
     483.000 |    459|
     484.000 |    459|
     485.000 |    459|
     486.000 |    459|
     487.000 |    459|
     488.000 |    459|
     489.000 |    459|
     490.000 |    459|
     491.000 |    459|
     492.000 |    459|
     493.000 |    459|
     494.000 |    459|
     495.000 |    459|
     496.000 |    459|
     497.000 |    459|
     498.000 |    459|
     499.000 |    459|
     500.000 |    459|

G:\S2 Astronomi PPA\SolEVORB\ApophisAndCloning_Rel0_500yForward\Batch1>
```

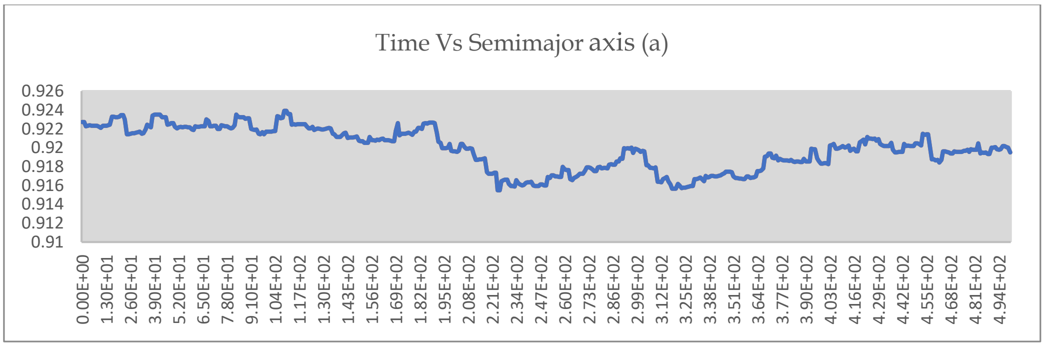
Figure 3. Orbit integration with the solevorb program

Table 2. Some close encounters experienced by apophis with planet earth

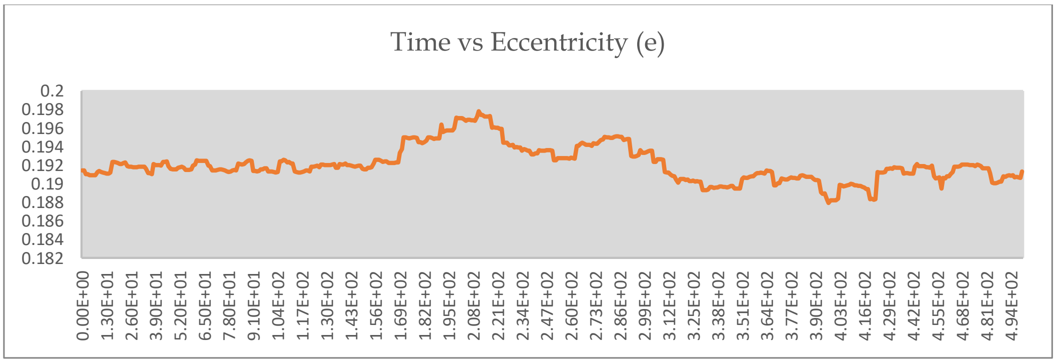
t enc	dm/R	Vp(km/s)	Energy	Planet	Asteroid
6.682	6.10	7.4	0.7578	3	1010
66.6795	6.60	7.31	0.7603	3	499
44.6789	10.90	6.76	0.7597	3	571
81.6781	14.00	6.56	0.7572	3	890

By adding the number of days to the initial date of calculation or initial epoch, we obtained that the first close encounter with the Earth will occur on April 14, 2029, at 14:25:26 (UT). In the Small-Body Database Lookup website, NASA stated that the close encounter will occur on April 13, 2029, at 21:46 (UT) with a minimal distance of 5.96 times the Earth's radius and a relative speed of 7.42 km/s. There are differences between our computations with those of NASA. Our results are about 16 hours later for the close encounter event with 0.14 times the Earth's radius farther for minimal distance, and a slower relative speed of 0.02 km/s.

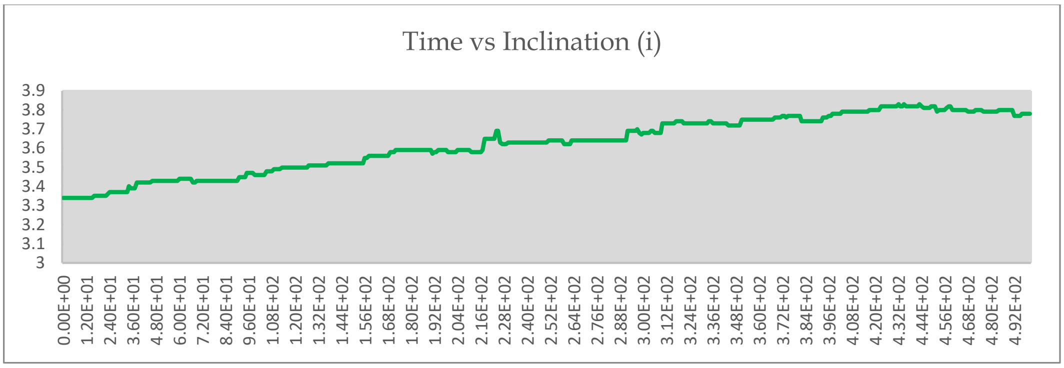
Further studies and significant analysis from photometry, spectroscopy, and radar ruled out the impact in 2029 and 2036 (Satpathy et al., 2022). Even the latest radar observations from Goldstone cancel out the risk of impact in 2068 and further show that Apophis poses no threat to Earth for at least another hundred years. This statement was also revealed from our results using Solevorb, that a close encounter within a distance less than 15 times the Earth's radius only occurs up to 81 years into the future. We also employed the Orbe integrator to check the consistency of our results. We found that our results from the two integrators are identical. Furthermore, we plot the orbital elements (*a*, *e*, *i*) as a time function, as seen in Figure 4 (a,b,c). These three parameters are not changed significantly for the next 500 years as no significant disturbances can change its orbit.



(a)



(b)

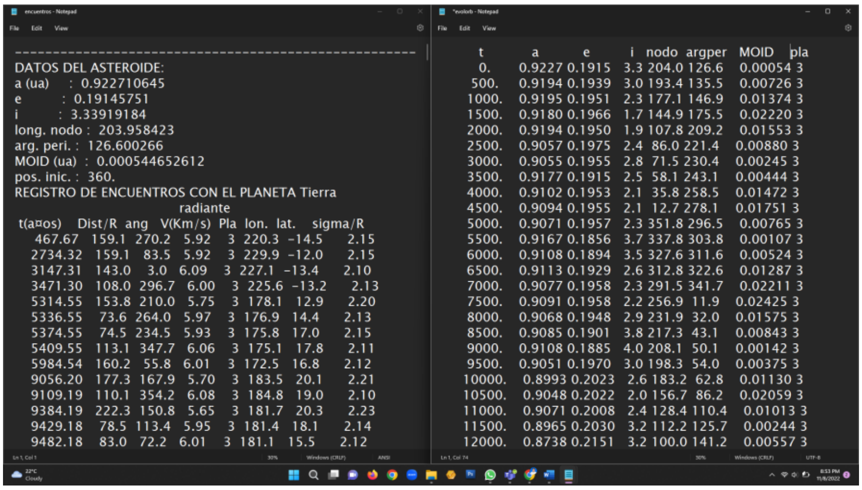


(c)

Figure 4. The evolution of *a*, *e*, and *i* of apophis for 500 years in the future.

To obtain more information needed to calculate the minimum orbital intersection distance (MOID) of an asteroid or comet with a particular planet, we employ the Colisionlab program. Using one of the outputs of the Colisionlab program as input for the grafica program, we can visualize the spatial distribution of encounters with respect to planets. Using the Evolucion program we can visualize the 2D orbit of the asteroid.

The first step in running the Colisionlab program is selecting a planet and entering the asteroid's orbital element. The program will then begin to calculate the asteroid's orbit due to planetary disturbances and the geometry of the encounter experienced by the asteroid with the planet. The program records all the computations in two files; those are encuentros.txt and evolorb.txt, as shown in Figure 5, which can be opened with any text editor.



```
encuentros - Notepad
------------------------------------------------------------
DATOS DEL ASTEROIDE:
a (ua)     :  0.922710645
e          :  0.19145751
i          :  3.33919184
long. nodo :  203.958423
arg. peri. :  126.600266
MOID (ua)  :  0.000544652612
pos. inic. :  360.
REGISTRO DE ENCUENTROS CON EL PLANETA Tierra
                          radiante
 t(a¤os)   Dist/R  ang   V(Km/s)  Pla  lon.   lat.   sigma/R
   467.67   159.1  270.2   5.92   3  220.3  -14.5    2.15
  2734.32   159.1   83.5   5.92   3  229.9  -12.0    2.15
  3147.31   143.0    3.0   6.09   3  227.1  -13.4    2.10
  3471.30   108.0  296.7   6.00   3  225.6  -13.2    2.13
  5314.55   153.8  210.0   5.75   3  178.1   12.9    2.20
  5336.55    73.6  264.0   5.97   3  176.9   14.4    2.13
  5374.55    74.5  234.5   5.93   3  175.8   17.0    2.15
  5409.55   113.1  347.7   6.06   3  175.1   17.8    2.11
  5984.54   160.2   55.8   6.01   3  172.5   16.8    2.12
  9056.20   177.3  167.9   5.70   3  183.5   20.1    2.21
  9109.19   110.1  354.2   6.08   3  184.8   19.0    2.10
  9384.19   222.3  150.8   5.65   3  181.7   20.3    2.23
  9429.18    78.5  113.4   5.95   3  181.4   18.1    2.14
  9482.18    83.0   72.2   6.01   3  181.1   15.5    2.12
```

```
*evolorb - Notepad
     t        a      e       i   nodo  argper   MOID    pla
     0.     0.9227 0.1915   3.3 204.0 126.6   0.00054 3
   500.     0.9194 0.1939   3.0 193.4 135.5   0.00726 3
  1000.     0.9195 0.1951   2.3 177.1 146.9   0.01374 3
  1500.     0.9180 0.1966   1.7 144.9 175.5   0.02220 3
  2000.     0.9194 0.1950   1.9 107.8 209.2   0.01553 3
  2500.     0.9057 0.1975   2.4  86.0 221.4   0.00880 3
  3000.     0.9055 0.1955   2.8  71.5 230.4   0.00245 3
  3500.     0.9177 0.1915   2.5  58.1 243.1   0.00444 3
  4000.     0.9102 0.1953   2.1  35.8 258.5   0.01472 3
  4500.     0.9094 0.1955   2.1  12.7 278.1   0.01751 3
  5000.     0.9071 0.1957   2.3 351.8 296.5   0.00765 3
  5500.     0.9167 0.1856   3.7 337.8 303.8   0.00107 3
  6000.     0.9108 0.1894   3.5 327.6 311.6   0.00524 3
  6500.     0.9113 0.1929   2.6 312.8 322.6   0.01287 3
  7000.     0.9077 0.1958   2.3 291.5 341.7   0.02211 3
  7500.     0.9091 0.1958   2.2 256.9  11.9   0.02425 3
  8000.     0.9068 0.1948   2.9 231.9  32.0   0.01575 3
  8500.     0.9085 0.1901   3.8 217.3  43.1   0.00843 3
  9000.     0.9108 0.1885   4.0 208.1  50.1   0.00142 3
  9500.     0.9051 0.1970   3.0 198.3  54.0   0.00375 3
 10000.     0.8993 0.2023   2.6 183.2  62.8   0.01130 3
 10500.     0.9048 0.2022   2.0 156.7  86.2   0.02059 3
 11000.     0.9071 0.2008   2.4 128.4 110.4   0.01013 3
 11500.     0.8965 0.2030   3.2 112.2 125.7   0.00244 3
 12000.     0.8738 0.2151   3.2 100.0 141.2   0.00557 3
```

Figure 5. Two Output Files of CollisionLab.exe: encuentros.txt and evolorb.txt

The second step is to visualize the spatial distribution of all encounters by executing the Grafica program. The distribution of Apophis' encounter with the Earth throughout the computation duration is shown in Figure 6.

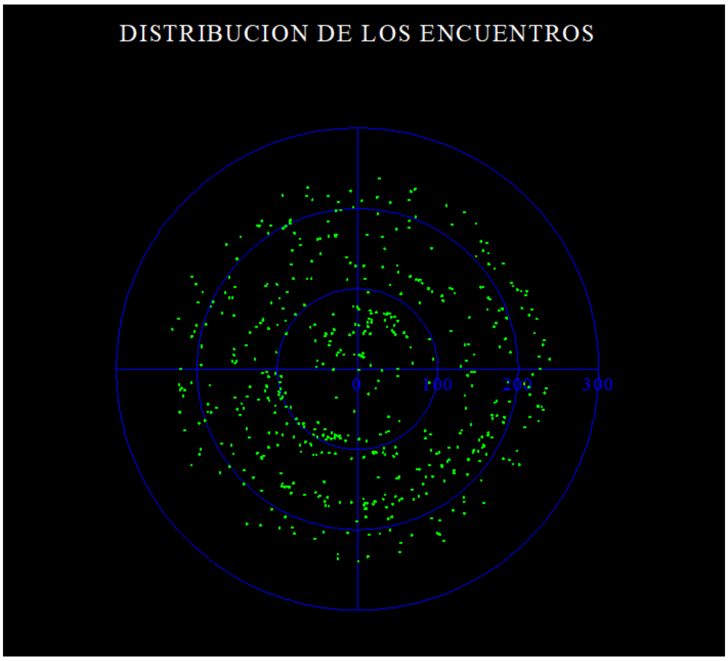
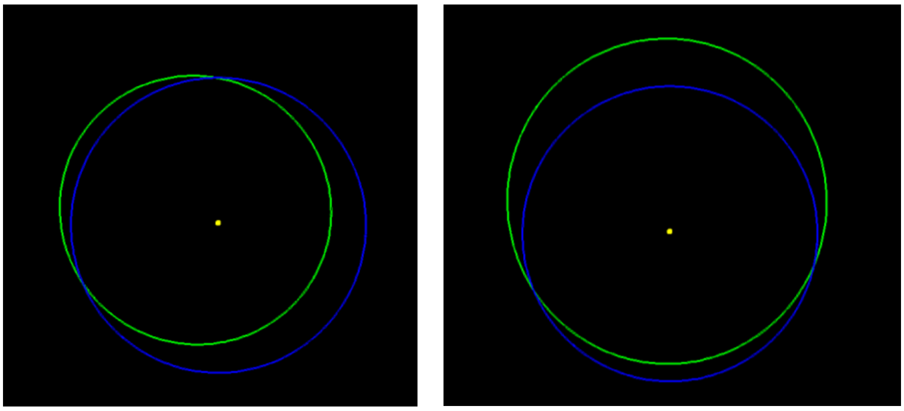


Figure 6. Apophis' encounter distribution with the earth

The third or the last step is to run the Evolucion program, which will display the evolution of the orbit over time: the blue ellipse represent the planet's orbit, the green ellipse for asteroid's orbit, the yellow dot represents the sun, the green vector represents the asteroid's perihelion direction, and the blue line represents the nodal line of the asteroid's orbit. The orbits comparison at the initial epoch with the one in 2029 can be seen in Figure 7, which was constructed using the Vis2orbit program from Gallardo (2017).


(a) (b)
Figure 7. Evolution of the apophis's orbit (a) at initial epoch (b) in 2029

Even though Apophis wouldn't harm Earth hundreds of years into the future, this asteroid remains an attractive "virtual impactor" for the planetary defense community. Apophis became the subject of a planetary defense exercise from December 2020 – March 2021 as it provides lessons on the ability to observe and model potential impactors (Reddy et al., 2022). Data products derived from astrometric observations are then fed into risk assessment models or orbit integrators, enabling real-time updating of probability calculations and possible impact locations. The availability of data from photometry, spectroscopy, and radar observations provides added value for assessing potential risks (Mainzer et al., 2021).

So that it can take preventive measures against the danger of asteroid collisions with the Earth, which NASA has successfully carried out in the trial of changing the asteroid's orbit with the kinetic impactor technique on NASA's Double Asteroid Redirection Test (DART Mission, 2022) mission on September 26, 2022, 23:14:24.183 UTC. DART is a low-cost spacecraft launching in 2021 that aims to navigate a crash into the small asteroid Dimorphos with 570 kilograms weight, and is approximately 1.8x1.9x2.5 meters (Raducan et al., 2022).

CONCLUSION

The results of orbit computation and the close encounter experienced by Apophis with planet Earth by employing the Solevorb program provide a predictive value that is not much different from the results of NASA. Amateur astronomers can use data from asteroid observations as input for the orbit integrator program to predict orbits both to the future and to the past.

REFERENCES

Andrews, V. P., Daou, D., & Johnson, L. N. (2021). The United States Planetary Defence Programme: nasa and the Planetary Defense Coordination Office. In *Legal Aspects of Planetary Defence* (pp. 66-85). Brill Nijhoff. https://doi.org/10.1163/9789004467606_008

Cheng, A. F., Rivkin, A. S., Michel, P., Atchison, J., Barnouin, O., Benner, L., ... & Thomas, C. (2018). AIDA DART asteroid deflection test: Planetary defense and science objectives. *Planetary and Space Science*, *157*, 104-115. https://doi.org/10.1016/j.pss.2018.02.015.

Chichura, P. M., Foster, A., Patel, C., Ossa-Jaen, N., Ade, P. A. R., Ahmed, Z., ... & Young, M. R. (2022). Asteroid measurements at millimeter wavelengths with the South Pole telescope. *The Astrophysical Journal*, *936*(2), 173. https://doi.org/10.3847/1538-4357/ac89ec

Davydov, V. I. (2021). Tunguska coals, Siberian sills and the Permian-Triassic extinction. *Earth-Science Reviews*, *212*, 103438. https://doi.org/10.1016/j.earscirev.2020.103438

Fauziah, A. N. I., Utama, J. A., & Simatupang, F. M. (2020). Jarak Minimum Orbit dan Tumbukan Populasi Asteroid dekat-Bumi dengan Planet Bumi. *Wahana Fisika*, *5*(1), 18-27. https://doi.org/10.17509/wafi.v5i1.23562

Gallardo, T. (2019). Strength, stability and three dimensional structure of mean motion resonances in the solar system. *Icarus*, *317*, 121-134. https://doi.org/10.1016/j.icarus.2018.07.002

Gallardo, T. (2017). Exploring the orbital evolution of planetary systems. *European Journal of Physics*, *38*(3), 035002. https://doi.org/10.1088/1361-6404/aa5e0c

Greenberg, R. (1982). Orbital interactions-A new geometrical formalism. *Astronomical Journal, vol. 87, Jan. 1982, p. 184-195.*, *87*, 184-195. https://dx.doi.org/10.1086/113095

Lang, K. R. (2011). *The Cambridge guide to the solar system*. New York: Cambridge University Press.

Little, H. (2022). The science communication of 'Don't Look Up'. *Journal of Science Communication*, *21*(5), C01. https://doi.org/10.22323/2.21050301

Mainzer, A., Abell, P., Bannister, M. T., Barbee, B., Barnes, J., Bell III, J. F., ... & Wright, E. L. (2021). The future of planetary defense in the era of advanced surveys. *Bulletin of the American Astronomical Society*, *53*(4), 259. https://doi.org/10.3847/25c2cfeb.ba7af878

Mashkova, I. V., Kostriykova, A. M., Trofimenko, V. V., & Slavnaya, A. I. (2019). Study of the zooplankton community as an indicator of the trophic status of reservoirs of the Chelyabinsk Region, Russia. In *IOP Conference Series: Earth and Environmental Science* (Vol. 344, No. 1, p. 012013). IOP Publishing. https://doi.org/10.1088/1755-1315/344/1/012013

Mulyani, A. B., Utama, J. A., & Iryanti, M. (2020). Resurfacing Asteroid Dekat-Bumi dengan Spektrum Tipe-Q akibat Papasan Dekat dengan Planet Bumi. In *Prosiding Seminar Nasional Fisika* (Vol. 1, No. 1, pp. 155-159).

Paris, R. (2020). Mega-tsunami deposits related to ocean island flank collapses and asteroid impacts. *Geological Records of Tsunamis and Other Extreme Waves*, 547-559. https://doi.org/10.1016/B978-0-12-815686-5.00025-0

Raducan, S. D., Jutzi, M., Davison, T. M., DeCoster, M. E., Graninger, D. M., Owen, J. M., ... & Collins, G. S. (2022). Influence of the projectile geometry on the momentum transfer from a kinetic impactor and implications for the DART mission. *International journal of impact engineering*, *162*, 104147. https://doi.org/10.1016/j.ijimpeng.2021.104147

Reddy, V., Kelley, M. S., Dotson, J., Farnocchia, D., Erasmus, N., Polishook, D., ... & Michel, P. (2022). Apophis Planetary Defense Campaign. *The Planetary Science Journal*, *3*(5), 123. https://doi.org/10.3847/PSJ/ac66eb

Riza, L. S., Fazanadi, M. N., Utama, J. A., Samah, K. A. F. A., Hidayat, T., & Nazir, S. (2022). SAX and Random Projection Algorithms for the Motif Discovery of Orbital Asteroid Resonance Using Big Data Platforms. *Sensors*, *22*(14), 5071. https://doi.org/10.3390/s22145071

Satpathy, A., Mainzer, A., Masiero, J. R., Linder, T., Cutri, R. M., Wright, E. L., ... & Kramer, E. (2022). NEOWISE Observations of the Potentially Hazardous Asteroid (99942) Apophis. *The Planetary Science Journal*, *3*(5), 124. https://dx.doi.org/10.3847/PSJ/ac66d1

Sokolov, L. L., Balyaev, I. A., Kuteeva, G. A., Petrov, N. A., & Eskin, B. B. (2021). Approaches and collisions of asteroids with the Moon and planets. In *Journal of Physics: Conference Series* (Vol. 1959, No. 1, p. 012047). IOP Publishing. https://doi.org/10.1088/1742-6596/1959/1/012047

Sokolov, L., Kuteeva, G., Petrov, N., & Eskin, B. (2019, November). Hazardous near-Earth asteroids approach. In *AIP Conference Proceedings* (Vol. 2171, No. 1, p. 130019). AIP Publishing LLC. https://doi.org/10.1063/1.5133286

Taşcan, M., & Ünal, İ. (2022). Activities design of Movements and Phases of the Moon: Spatial skill and academic achievement development. *Istraživanja u pedagogiji*, *12*(2), 375-390.

Thiry, N., & Vasile, M. (2016). Statistical multicriteria evaluation of asteroid deflection methods. In *Proceedings of the International Astronautical Congress, IAC . International Astronautical Federation (IAF), MEX*.

Utama, J. A., & Rusdiana, D. (2020). Frekuensi Tumbukan Populasi Asteroid dekat-Bumi Berukuran Kecil terhadap Planet-Planet Kebumian. In Prosiding Seminar Nasional Fisika (Vol. 1, No. 1, pp. 275-280).

Vernazza, P., Ferrais, M., Jorda, L., Hanuš, J., Carry, B., Marsset, M., ... & Socha, L. (2021). VLT/SPHERE imaging survey of the largest main-belt asteroids: Final results and synthesis. *Astronomy & Astrophysics*, *654*, A56. https://doi.org/10.1051/0004-6361/202141781