New Impact Solutions for Potentially Hazardous Asteroid (99942) Apophis

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We computed impact solutions of the potentially dangerous asteroid (99942) Apophis based on 4022 optical observations from March 15, 2004 to January 1, 2015, and 7 radar observations from March 15.10789 UTC through March 28.089569 UTC, 2013. Using the freely available ORBFIT Software Package, we can follow its orbit forward in the future searching for close approaches with the Earth, which can lead to possible impacts up to 2110. The possible impact path of risk for 2068 is presented.

1 List of Possible Impacts

We computed possible impact solutions according to our method Wlodarczyk (2015, 2013) which is based on the method of Sitarski (2006), Milani and the NEODyS Team, included in the ORBFIT software. The covariance cloning is based on the Line of Variations (LOV) with the largest eigenvalue, where σ LOV denotes the position of an asteroid on the orbit along the line of variations in σ space (Milani et al., 2005a,b).

We searched for potential impacts out to σ LOV = 5, similarly to the Sentry System of the JPL NASA and the NEODyS's CLOMON2 System for the case of the asteroid (99942) Apophis.

To search for possible impact solutions, we computed 3000 virtual asteroids (VAs) on both sides of the LOV which gives 6001 VAs and propagated their orbits to JD 2492000.5 TDT, i.e. October 7, 2110.

Table 1 lists possible impacts of the asteroid (99942) Apophis computed with the NEODyS method. It is well visible that probability of the potential impact of the asteroid (99942) Apophis and the possible dates of impact depend on adopted dynamical model with included non-gravitational effects in the motion of asteroid based on cometary approach.

In the case of asteroid (99942) Apophis we searched for potential impact solution using value of the non-gravitational parameters from A2=$-50 \times 10^{-15} au/d^2$ to A2=$+50 \times 10^{-15} au/d^2$ with the step of $1 \times 10^{-15} au/d^2$. Hence, we found that are many possible impact solutions in the range (-48.0, +46.0)$\times 10^{-15} au/d^2$.

Table 1 lists for each adopted non-gravitational parameter A2: date of possible impact (year, month and day), σ LOV and impact probability. The impact solutions are computed for the parameter σ LOV in the range (-5, +5).

In all solutions presented in Table 1 computed impact velocity, Vimpact, i.e. a velocity of the asteroid (99942) Apophis at atmospheric entry, is of about 12.6 km/s, and the impact energy is of about 1200 MT.

Date of impact	σ LOV	Impact Probability
	A2=−48	
2105/04/11.910	-2.2334	1.29E-07
	A2=−47	
2084/09/23.078	4.2051	1.93E-10
	A2=−23	
2075/04/13.220	-1.4197	1.69E-06
2107/04/14.174	-1.3383	2.01E-07
	A2=−22	
2056/04/13.094	3.1112	8.86E-08
2060/04/13.093	3.4375	9.04E-09
2068/04/13.196	4.1899	2.46E-10
	A2=−21	
2055/04/13.816	-2.5685	7.64E-08
2056/04/13.094	-3.1304	8.36E-08
2065/04/13.131	-0.5361	5.90E-06
	A2=−20	
2068/04/12.632	-3.1233	1.98E-06
2069/04/12.726	-3.1293	1.70E-09
2076/04/12.699	-0.1531	2.45E-05
2077/04/13.112	-3.2342	3.42E-08
2087/04/13.397	-3.1873	8.88E-09
2103/04/14.304	-3.3371	5.90E-08
	A2=−11	
2064/04/13.026	0.7276	1.69E-06
2075/04/13.210	0.4676	4.22E-06
	A2=−10	
2055/04/13.821	-1.4199	7.61E-07
2056/04/13.094	-1.9818	1.57E-06
2060/04/13.093	-1.6555	8.46E-07
2065/04/13.137	0.6125	5.66E-06
2066/04/13.586	0.5106	2.68E-06
2068/04/13.199	-0.8769	8.97E-07
2068/04/12.632	4.2662	2.91E-08
2077/04/13.112	4.1552	1.14E-09
2078/04/13.376	0.6805	5.62E-06
2079/04/14.104	-0.9582	2.60E-07
2087/04/13.397	4.2021	2.09E-10
2090/10/16.580	0.2645	1.27E-06
2098/10/16.481	0.2150	7.53E-06
2100/04/13.594	1.1494	1.50E-06
2103/04/14.302	4.0522	4.20E-09
	A2=+1	
2068/10/15.327	2.8819	2.59E-07
2105/10/16.309	2.8943	5.61E-07
	A2=+2	
2068/10/15.325	-1.1289	8.80E-06
2086/10/15.627	-1.1221	5.74E-07
2105/10/16.294	-1.1165	1.92E-05
	A2=+11	
2102/04/14.078	1.2461	2.04E-06
2104/10/31.604	1.4237	6.24E-06
	A2=+12	
2102/04/14.067	-2.8046	8.65E-08
	A2=+26	
2085/10/15.428	2.6778	2.48E-08
	A2=+27	
2085/10/15.425	-1.3098	3.79E-07
2085/09/03.785	3.8732	9.04E-11
2088/09/28.799	3.4593	9.55E-09
2099/09/30.289	3.4473	9.70E-09
2100/10/16.547	1.9576	5.52E-08
2109/09/03.039	3.8651	1.64E-08
	A2=+29	
2088/09/28.805	-4.5178	1.54E-10
2099/09/30.283	-4.5299	7.65E-11
2109/09/03.034	-4.1108	7.28E-09
	A2=+44	
2069/10/15.599	4.8708	2.56E-10
2087/10/15.856	4.8820	1.08E-11
2106/10/16.489	4.9031	1.05E-10
	A2=+45	
2069/10/15.600	0.8714	2.50E-05
2086/10/15.649	0.8779	3.18E-07
2087/10/15.869	0.8826	1.08E-06
2106/10/16.491	0.9037	1.12E-05
2109/04/12.696	1.8109	7.00E-07
	A2=+46	
2069/10/15.597	-3.1285	2.75E-07
2106/10/16.488	-3.0960	1.32E-07
2109/04/12.687	-2.1877	3.31E-07

Table 1: Asteroid (99942) Apophis. Possible impact solutions computed for different non-gravitational parameter A2 searched between A2=$-50 \times 10^{-15} au/d^2$ to A2=$+50 \times 10^{-15} au/d^2$ with the step of $1 \times 10^{-15} au/d^2$ in $\times 10^{-15} au/d^2$.

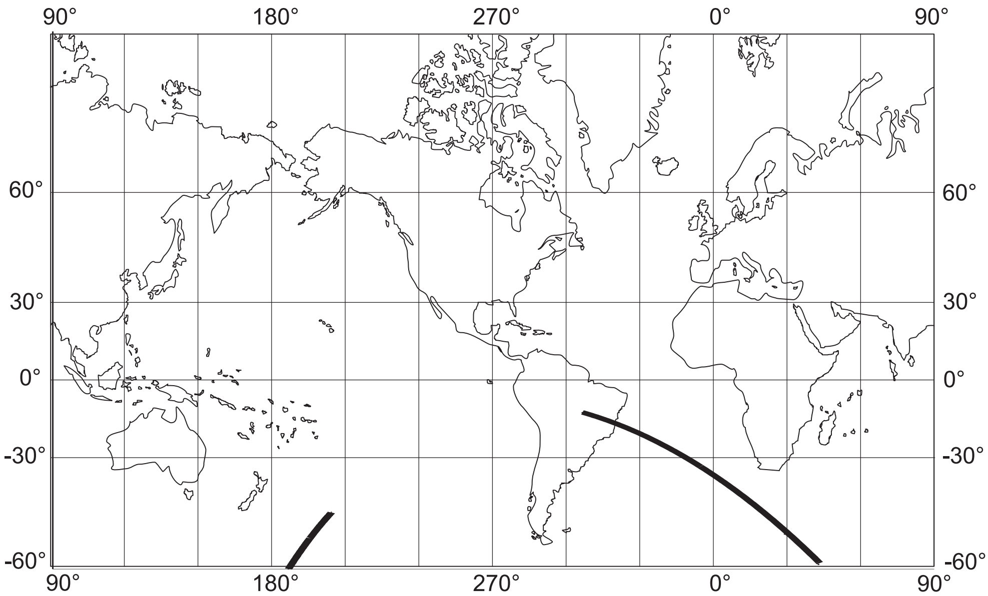

Fig. 1: The path of risk where the asteroid (99942) Apophis could impact in the year 2068 as computed with nongravitational parameter A2=$-20 \times 10^{-15} au/d^2$ - see Table 1.

The NEODyS site[1] computed risk table for Apophis using 4105 optical observations (of which 87 are rejected as outliers) from 2004-03-15.109 to 2013-05-07.150, and at top of this list is possible impact in 2068. However, the JPL NASA site[2] presents impact solutions based on 13 radar delay, 7 Doppler, and 4147 optical observations spanning 3635.5 days (2004-Mar-15.126289 to 2014-Feb-26.64670). They computed the greatest impact probability in 2068. Hence we take into account our impact solution in 2068.

The path of risk of the possible impact in the year 2068 is shown in Fig. 1. There is a cloud of orbit solutions, most of which do not impact the Earth. One part of that cloud gives impact solutions. Most of the clones spread out along-track. Note that path of risk is computed for 5-σ uncertainty. Both ends of the path of risk have lower impact probability than the central places. Hence the probability of hitting Brazil by Apophis is very low.

We present computed impact probabilities without discussion about probabilities of different adopted parameter A2. They can be read as the raw data waiting for physical parameters of the asteroid (99942) Apophis.

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