AEGIS: ESA'S PLANETARY DEFENCE OFFICE ORBIT DETERMINATION AND IMPACT MONITORING SOFTWARE

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ABSTRACT

The goal of impact monitoring is to determine whether a near-Earth object could possibly impact the Earth or not. It is essential to perform this activity as soon as new observations are released, in order to improve the orbit of possibly impacting asteroids by a quick follow-up campaign. Here we introduce Aegis, an automated orbit determination and impact monitoring system developed by SpaceDyS s.r.l. under ESA contracts, and operated by the ESA NEO Coordination Centre.

Keywords: near-Earth asteroids; impact monitoring; Space Safety; ESA Operations.

1. INTRODUCTION

One of the main goals of the ESA NEO Coordination Centre (NEOCC) is the computation of the orbits of near-Earth objects (NEOs) and their probability of impact with the Earth. These activities are carried out by the Risk Assessment Pillar, one of the three pillars of the ESA Planetary Defence Office (PDO) [1]. To achieve this goal the NEOCC operates Aegis, an automated orbit determination and impact monitoring system developed by SpaceDyS s.r.l. through industrial contracts from ESA. This system is completely independent from the Sentry and Clomon-2 systems, operated by NASA and NEODyS, respectively. The Aegis system updates the local astrometric database by checking the observations issued by the Minor Planet Center (MPC) on a daily basis, and provides a catalog of NEOs which comprises orbits with their uncertainties, some physical properties, observations and residuals, close approaches, and ephemerides.

More importantly, it computes the impact probabilities of NEOs in the next 100 years, and the results are collected in the so-called Risk List. When the impact probability is high enough, the software is able to compute the related impact corridor. All the data generated by Aegis is publicly available at the NEOCC web portal[1].

In addition, Aegis is used to produce the input of several tools and services available on the portal, such as all the tools of the NEO Toolkit, and the ephemerides generation service. Aegis also supports several additional activities carried out at the NEOCC, and it will be used for the observation scheduling of the Flyeye telescope.

2. ORBIT DETERMINATION

The orbital elements of an asteroid are computed by fitting the astrometrical observations to the predictions calculated with a dynamical model. The fit is performed with a least-square method aimed to minimize the residuals, i.e. the differences between the observations and the simulated predictions. In Aegis, the solution of the minimum problem is computed with a differential correction algorithm. The differential corrector is also endowed with an automatic procedure for the rejection of outliers observations, that are not taken into account in the final fit. The orbit determination procedure makes use of an astrometric error model based on [2]. Initial conditions

[1] `https://neo.ssa.esa.int/`

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for the differential corrector can be either retrieved from the MPC catalog, or computed from scratch by using the Gauss or Laplace initial orbit determination methods, that are implemented in Aegis. Details of the algorithms implemented in the software can be found in [3].

The dynamical model used in the orbit determination and propagation includes the gravitational attraction of the Sun, the eight planets, the Moon, the 16 most massive main-belt asteroids, and Pluto. The software makes use of the JPL Planetary and Lunar Ephemerides DE441 to retrieve the positions of massive objects. In addition, the parameterized post-Newtonian relativistic contributions, and the oblateness of the Sun and the Earth are added to the force field. Non-gravitational forces, such as the Yarkovsky effect and the solar radiation pressure, can also be added to the dynamical model in special cases, and their magnitude can be estimated through the orbit determination process.

The propagation of the orbit of an asteroid is performed with a multistep predictor-corrector integration scheme. The general strategy for the propagation is to split it into a sequence of local propagations [4]. Each local propagation computes the solution of a perturbed two-body problem, with a certain primary body of attraction. When the object gets sufficiently close to a third body, that body becomes the new primary and another local propagation is started. During planetary close approaches the propagation is carried out by using the Kustaanheimo-Stiefel regularization [5], in order to reduce the numerical error.

3. IMPACT MONITORING

The aim of impact monitoring is to understand whether the confidence region of the orbit of an NEA contains some virtual impactors or not. To this purpose, the confidence region is sampled with a finite number of Virtual Asteroids (VAs), all compatible with the observations, and then propagated in the future to search for possible impacts.

In the operative scenario, Aegis uses the Line Of Variations (LOV) method [3] for the sampling of the confidence region. The LOV method is a geometrical 1-dimensional sampling that takes advantage of specific properties of the confidence region of NEAs orbit. In fact, the confidence region is usually stretched along a particular direction, which is the direction of largest uncertainty. Other directions have a much smaller uncertainty if compared to the previous one. The LOV method relies on the sampling of the direction of largest uncertainty with a small number of VAs, typically of the order of a few thousands. VAs are propagated in the future for 100 years, and close approaches with the Earth are recorded as a set of points on the Target Plane (TP). If a Virtual Impactor (VI) is found, the impact probability is estimated through a 1-dimensional Gaussian distribution. Details of these methods and algorithms can be found in [3] and references therein. In addition, the Torino Scale [6] and the Palermo Scale [7] are computed for each VI.

Apart from the operative scenario, Aegis is also able to perform full Monte Carlo simulations. The confidence region is sampled with a large number N of VAs by using the covariance matrix of the orbit, that are later propagated in the future to search for impactors. This method can typically find VIs with an impact probability of the order $\sim 1/N$, and therefore it is not suitable to be used in an operative scenario. However, it generally relies on less assumptions than then LOV method, and therefore it is useful to check the results when the probabilities of impact are relatively high.

4. AEGIS OPERATIONS

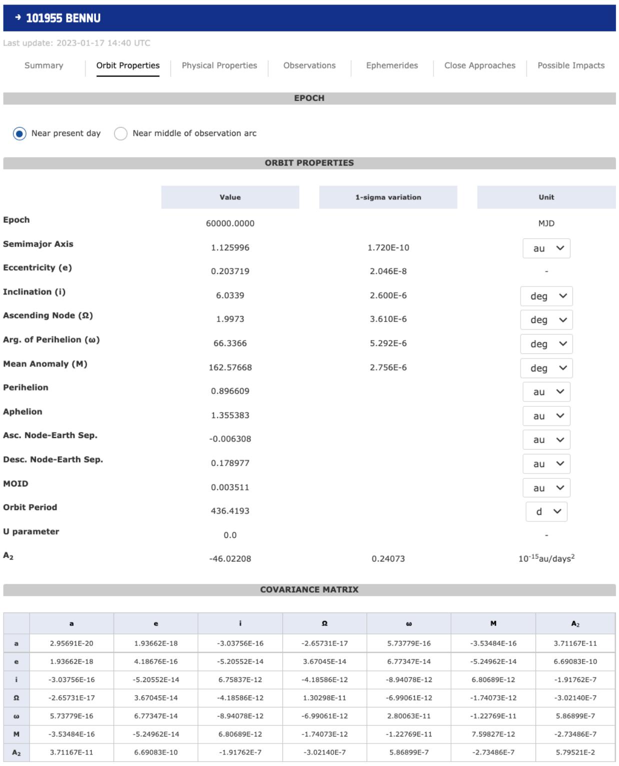
4.1. Orbit catalog

The Aegis software is used to maintain the orbit catalog of all asteroids, both NEAs and non-NEAs. NEAs are added to the catalog whenever a discovery MPEC is released by the MPC, and their orbits are updated at every daily orbit update of the MPC. On the other hand, the catalog and the orbits of non-NEOs are updated at every monthly update of the MPC. The orbit of an asteroid is computed at both the current epoch, and at the weighted average epoch of the observations. Together with the orbital elements, the covariance and the normal matrix obtained from the orbit determination algorithm are provided by the software. Orbits are provided to the user in two formats: 1) in equinoctal elements, and 2) in Keplerian elements. All the orbital data is publicly available through the NEOCC web portal, and it can be accessed by the user either from the web-page dedicated to each asteroid, or through the HTTPS APIs[2]. In addition to orbital data, the page of an individual asteroid provides information about observations and close approaches with main bodies. The total length of the observational arc, the RMS of the residuals, the number of observations used in the fit, and the list of observations of the object with the corresponding residuals, are all available to the user from this page. Figure 1 shows an example of the page with orbital information about asteroid (101955) Bennu.

4.2. Risk list

The Aegis software is used to generate the NEOCC Risk List[3]. The Risk List is a catalog of all NEOs for which a non-zero impact probability has been computed. Each entry contains details on the particular Earth approach which poses the highest risk of impact, as expressed by the Palermo Scale. It includes its date, size, velocity and probability. Impact history data can be accessed in tabular and graphical form. In most cases, the size presented in the table is estimated indirectly from the absolute magnitude, and flagged with an asterisk. When a better measurement is available in the literature, it replaces the estimated value. By default, entries are sorted by the maximum Palermo Scale value. Figure 2 displays the first

[2] `https://neo.ssa.esa.int/computer-access`
[3] `https://neo.ssa.esa.int/risk-list`



101955 BENNU

Last update: 2023-01-17 14:40 UTC

Summary | Orbit Properties | Physical Properties | Observations | Ephemerides | Close Approaches | Possible Impacts

EPOCH

Near present day — Near middle of observation arc

ORBIT PROPERTIES

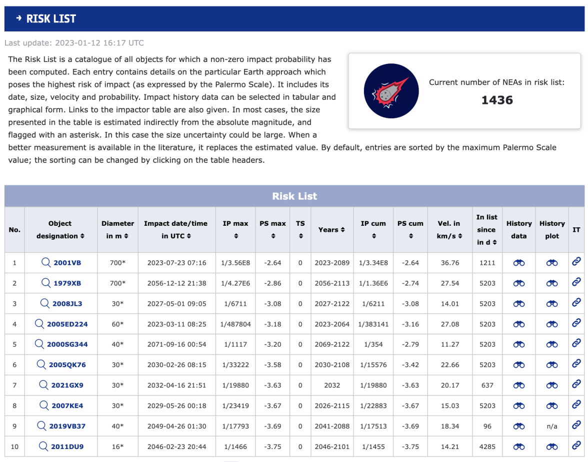
	Value	1-sigma variation	Unit
Epoch	60000.0000		MJD
Semimajor Axis	1.125996	1.720E-10	au
Eccentricity (e)	0.203719	2.046E-8	-
Inclination (i)	6.0339	2.600E-6	deg
Ascending Node (Ω)	1.9973	3.610E-6	deg
Arg. of Perihelion (ω)	66.3366	5.292E-6	deg
Mean Anomaly (M)	162.57668	2.756E-6	deg
Perihelion	0.896609		au
Aphelion	1.355383		au
Asc. Node-Earth Sep.	-0.006308		au
Desc. Node-Earth Sep.	0.178977		au
MOID	0.003511		au
Orbit Period	436.4193		d
U parameter	0.0		-
A_2	-46.02208	0.24073	10^{-15}au/days^2

COVARIANCE MATRIX

	a	e	i	Ω	ω	M	A_2
a	2.95691E-20	1.93662E-18	-3.03756E-16	-2.65731E-17	5.73779E-16	-3.53484E-16	3.71167E-11
e	1.93662E-18	4.18676E-16	-5.20552E-14	3.67045E-14	6.77347E-14	-5.24962E-14	6.69083E-10
i	-3.03756E-16	-5.20552E-14	6.75837E-12	-4.18586E-12	-8.94078E-12	6.80689E-12	-1.91762E-7
Ω	-2.65731E-17	3.67045E-14	-4.18586E-12	1.30298E-11	-6.99061E-12	-1.74073E-12	-3.02140E-7
ω	5.73779E-16	6.77347E-14	-8.94078E-12	-6.99061E-12	2.80063E-11	-1.22769E-11	5.86899E-7
M	-3.53484E-16	-5.24962E-14	6.80689E-12	-1.74073E-12	-1.22769E-11	7.59827E-12	-2.73486E-7
A_2	3.71167E-11	6.69083E-10	-1.91762E-7	-3.02140E-7	5.86899E-7	-2.73486E-7	5.79521E-2

Figure 1. Example of the page containing orbital information, where the orbit of asteroid (101955) Bennu is shown.

10 entries of the Risk List as shown on the NEOCC web portal on 12th January 2023.



RISK LIST

Last update: 2023-01-12 16:17 UTC

The Risk List is a catalogue of all objects for which a non-zero impact probability has been computed. Each entry contains details on the particular Earth approach which poses the highest risk of impact (as expressed by the Palermo Scale). It includes its date, size, velocity and probability. Impact history data can be selected in tabular and graphical form. Links to the impactor table are also given. In most cases, the size presented in the table is estimated indirectly from the absolute magnitude, and flagged with an asterisk. In this case the size uncertainty could be large. When a better measurement is available in the literature, it replaces the estimated value. By default, entries are sorted by the maximum Palermo Scale value; the sorting can be changed by clicking on the table headers.

Current number of NEAs in risk list:
1436

Risk List

No.	Object designation	Diameter in m	Impact date/time in UTC	IP max	PS max	TS	Years	IP cum	PS cum	Vel. in km/s	In list since in d	History data	History plot	IT
1	2001VB	700*	2023-07-23 07:16	1/3.56E8	-2.64	0	2023-2089	1/3.34E8	-2.64	36.76	1211			
2	1979XB	700*	2056-12-12 21:38	1/4.27E6	-2.86	0	2056-2113	1/1.36E6	-2.74	27.54	5203			
3	2008JL3	30*	2027-05-01 09:05	1/6711	-3.08	0	2027-2122	1/6211	-3.08	14.01	5203			
4	2005ED224	60*	2023-03-11 08:25	1/487804	-3.18	0	2023-2064	1/383141	-3.16	27.08	5203			
5	2000SG344	40*	2071-09-16 00:54	1/1117	-3.20	0	2069-2122	1/354	-2.79	11.27	5203			
6	2005QK76	30*	2030-02-26 08:15	1/33222	-3.58	0	2030-2108	1/15576	-3.42	22.66	5203			
7	2021GX9	30*	2032-04-16 21:51	1/19880	-3.63	0	2032	1/19880	-3.63	20.17	637			
8	2007KE4	30*	2029-05-26 00:18	1/23419	-3.67	0	2026-2115	1/22883	-3.67	15.03	5203			
9	2019VB37	40*	2049-04-26 01:30	1/17793	-3.69	0	2041-2088	1/17513	-3.69	18.34	96		n/a	
10	2011DU9	16*	2046-02-23 20:44	1/1466	-3.75	0	2046-2101	1/1455	-3.75	14.21	4285			

Figure 2. First 10 NEOs of the NEOCC Risk List, as of 12th January 2023.

4.3. Ephemerides service

The NEOCC provides the user an ephemerides request service, and the Aegis software is used to take care of the computation requested. The ephemerides service is available through an HTTPS API, where the user has to specify: 1) the object for which the ephemerides are needed; 2) the code of the observatory from which it will be observed; 3) the initial and the final epochs; 4) the timestep for the output. The user will then receive a table containing the equatorial coordinates as a function of time, the apparent motion, and the sky plane error.

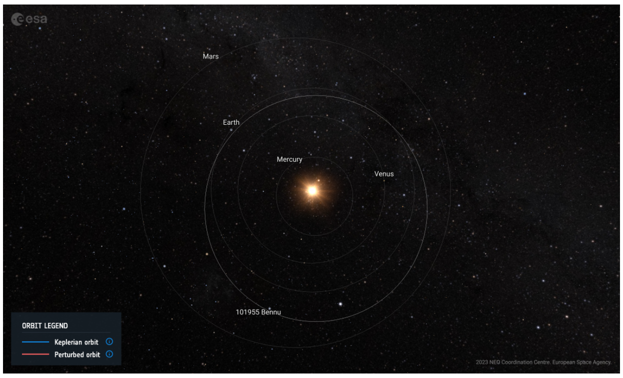


Figure 3. Orbit of (101955) Bennu as shown by the OVT of the NEOCC NEO Toolkit.

4.4. NEO Toolkit

The NEO Toolkit [4] is a new set of astronomical tools designed by the NEOCC. The toolkit is composed by four complementary tools, each of them focused on a different goal. The Observation Planning Tool (OPT) provides users with precise ephemerides and observational data from NEOs to help them planning and scheduling observations in forthcoming nights. The Sky Chart Display Tool (SCDT) supports observations by producing a visualisation of the orbits of NEOs in the sky as observed from any location in the world. The Orbit Visualisation Tool (OVT) allows visualising the orbits of one or more simultaneous asteroids and comets in a 3D environment. The Flyby Visualisation Tool (FBVT) offers a high accuracy visualisation of NEOs that have one or more close approaches with the Earth, shown also in a 3D environment. Figure 3 depicts the orbit of (101955) Bennu, as shown by the OVT.

4.5. Impact corridor

In the case a VI with a probability of impact larger than 10^{-3} is found, the Aegis software is able to compute the impact corridor with the Earth, which shows the possible impact area on the surface. The algorithm used for this computation is described in [8]. The impact corridor typically shows three concentric ellipsoids, corresponding to the impact area determined at 1σ, 3σ, and 5σ level.

The impact corridor is an effective tool to ease the

[4] `https://neo.ssa.esa.int/neo-toolkit`

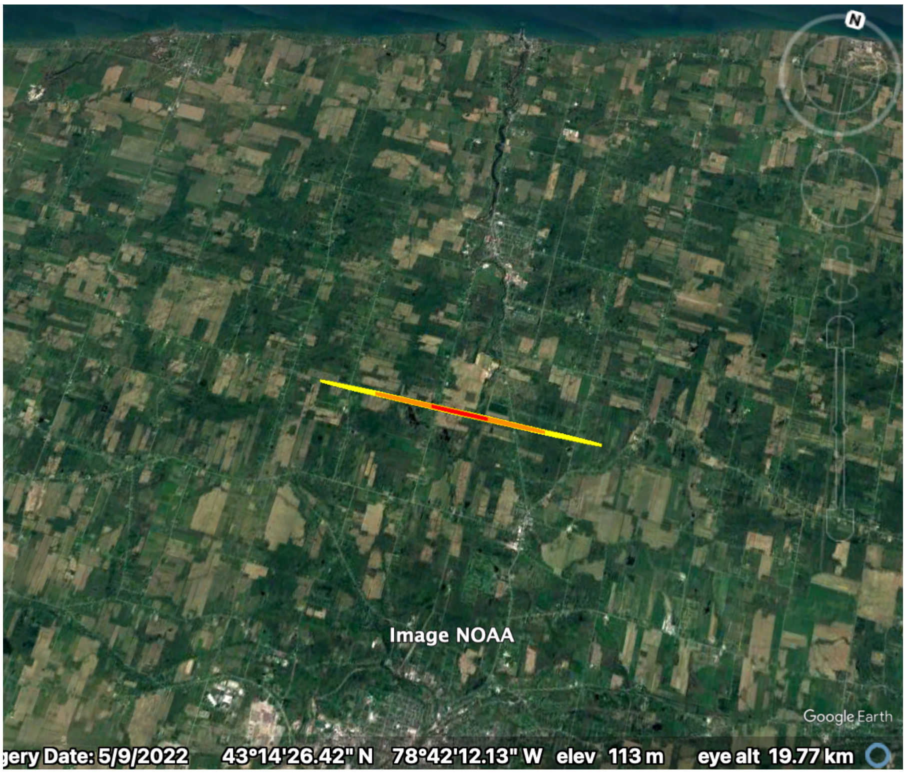


Figure 4. Impact corridor of 2022 WJ1 on the ground, a small NEO impacted with the Earth on 19th November 2022. The red, orange, and yellow areas represent the impact corridor at 1σ, 3σ, and 5σ level, respectively. Note that the last part of the numerical integration has been performed without taking into account the atmospheric drag.

communication of the possible impact threat to local emergency response facilities. In the case the impact does not pose any danger to people and infrastructures, it can still be useful to schedule an observation campaign of the fireball event. Figure 4 shows the impact corridor computed for asteroid 2022 WJ1, a small NEO that impacted the Earth on 19th November 2022 a few hours after its discovery.

5. OTHER ACTIVITIES SUPPORTED BY AEGIS

In addition to daily operations, Aegis is foreseen to be used as a support for the Risk Assessment Pillar to carry out other activities in NEOs research. Aegis and its predecessor, AstOD, have been used already in several such activities, including: 1) the analysis of the orbital stability of the second Earth Trojan asteroid (614689) 2020 XL5 [9]; 2) the negative observation exercise of 2010 RF12; 3) the development of an automated Yarkovsky effect detection procedure; 4) the update of the risk assessment of (29075) 1950 DA and of (99942) Apophis; 5) the Apophis 2021 campaign exercise. In the near future, Aegis will also be used as a support for the observation scheduling of the Flyeye telescope.

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