

SPACE SITUATIONAL AWARENESS PROGRAMME: ENHANCED NEO PROPAGATOR (NEOPROP2)

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ABSTRACT

The overall aim of the Space Situational Awareness (SSA) Preparatory Programme is to support the European independent utilization of, and access to, space for research or services, through providing timely and quality data, information, services and knowledge regarding the environment, the threats and the sustainable exploitation of the outer space surrounding our planet Earth.

Currently there are over 600.000 asteroids known in our Solar System, where more than 13.000 of these are NEOs. They could potentially hit the Earth and depending on their size could produce considerable damage. For this reason, NEOs deserve active detection and tracking efforts. The role of the SSA programme is to provide warning services against potential asteroid impact hazards including discovery, identification, orbit prediction and civil alert capabilities.

In 2012, Astos Solutions developed for ESA a new orbital propagator algorithm in order to assess the potential risk of impact of a NEO. The objective of that activity was to come up with a different trajectory prediction algorithm, which allows an independent validation of the current algorithms within the SSA-NEO segment (e.g. NEODyS, JPL Sentry System). Analytical and numerical algorithms were developed in order to assess minimum orbital intersection distances and close approaches with other celestial bodies.

In 2015, a new version of the tool was developed to improve and extend its functionalities. The following new algorithms were added:

- Estimation of impact probabilities as Torino and Palermo scale values, after propagating virtual asteroids computed along the line of variation. These figures are important characteristics for Governments to identify potentially catastrophic scenarios and to prepare counter-measures or evacuations.
- New orbital perturbations (e.g. Poynting-Robertson effect, solar radiation pressure, outgassing) to improve the propagator accuracy and to allow the identification and propagation of any celestial body (not only NEOs but also moons, comets, planets, etc).

The pre-existing algorithms have been further improved in order to increase the performance and reduce the need for human intervention. Robust and redundant preliminary orbit determination techniques have been added in order to deal with very long and disrupted observational arcs, which usually would require a manual split of the observations.

Moreover, a graphical user interface has been developed in order to ease the setup of a new scenario, collecting observations and physical properties of the object to be analyzed and allowing the comparison of the results with those provided by other systems (e.g. NEODyS, JPL Sentry).

1. ARCHITECTURE

NEOProp2 improves and extends the functionalities of the NEOProp software. In this paper, only the new features are presented and discussed. Detailed information about existing functionalities of the tool can be found in [1].

As its predecessor, NEOProp2 has two separate modules:

1. The Analytical Module makes use of analytical algorithms in order to rapidly assess the impact risk of a NEO. Orbit determination algorithms determine the initial state, along with its uncertainty, and the minimum orbital intersection distances (MOID) of the NEO (computed analytically). If the MOID is under a certain threshold, a numerical analysis is recommended.
2. The Numerical Module makes use of numerical algorithms in order to refine and to better assess the impact probabilities of a NEO. The initial state provided by the Analytical Module is used for the numerical propagation of the trajectory, which can be run in two modes: one faster, in order to get a quick estimate of the trajectory (fast analysis) and one more precise, taking into consideration more detailed and complex models (complete analysis). Along with the numerical propagation of the nominal state, Virtual Asteroids (VAs) can be numerically propagated in order to determine the (numerical) MOID and assess the impact risk of the asteroid, in case at least one virtual impactor is found. This MOID computation differs from the

one performed by the Analytical Module since it takes into consideration the full dynamics of the problem (all the relevant perturbations).

An aspect common to both the modules is the usage of multi-threading. The tool is able to detect how many threads are available and to assign them in order to parallelize some computations.

Moreover, in order to improve the usability of the tool a Graphical User Interface (GUI) has been developed. It allows the user to quickly create a new scenario and to easily retrieve from internet observations and physical properties for the NEO to be analyzed. With the GUI, the user can run the modules without having to use the command-line interface and can rapidly visualize and export the most important results in an html file. If requested, the GUI can retrieve the orbital elements, MOID and risk figures from the NEODyS and Sentry systems and compare them with the results obtained by NEOProp2.

2. ANALYTICAL MODULE

This module allows determining the initial state (with uncertainty) of a NEO from a set of observations. First a preliminary Gauss algorithm is run in order to get a first solution of the orbit determination problem using only optical observations.

The Gauss method needs only three observations (triplet) in order to compute a preliminary initial state. Then a Linear Least Square (LLS) technique is used to refine the solution and minimize the root mean square (RMS). As any other least square technique, an initial guess is required in order to start the computation. The weak point of such technique is the initial guess itself. If it is too poor (too far from the real solution), the least square method may fail to converge.

In the previous version of the tool, the LLS technique did not always converge, especially when there were many observations, discontinuities or close approaches within the observation set. A first solution to this problem consisted in splitting the observations into shorter arcs, which would start to constraint the solution. In this way the Gauss method can work with consistent observations and find more easily a good solution. The set of observations had to be manually split into intervals, whereas first the orbit determination was performed just with the oldest interval and then further arcs were gradually added, always using the results of the previous run as initial guess.

Since this approach was time consuming and depended mostly on the ability of the user, a different algorithm able to 'help' the Gauss method, by weighting and selecting more carefully the initial observations to be used, has been implemented. In this way the output of the Gauss method may be more robust and good enough to allow the LLS technique to converge.

The new weighting algorithm identifies and weights all triplets matching the following criteria:

- the time difference between two consecutive observations must be at least 0.03 days;
- the time difference between two consecutive observations must be maximum 150 days;
- the weight (computed considering an ideal time difference between two consecutive observations equal to 20 days) assigned to a triplet must be lower than the weight assigned to the previously tested triplets;
- the statistical RMS assigned to the observatory related to each observation must be lower than 4.0 arcsec.

As many threads as possible are used to evaluate the triplets. The search is stopped once the specified minimum RMS is reached. If not reached, the triplet with the lowest RMS is used. Then the preliminary solution is improved by mean of a LLS technique, which eventually considers also radiometric observations.

Since it is not possible to guarantee the LLS convergence, an outer loop, able to restart the whole orbit determination process every time it fails, has been implemented. If the LLS technique does not converge, the Gauss method is rerun and a new preliminary solution is found (without using observations used for previous preliminary solutions). After 30 unsuccessful attempts the software stops, saying that the maximum number of iterations has been reached without obtaining convergence. This can happen if observations are not good enough, or if an abrupt event (e.g. close approach) modified the orbit within the observational arc.

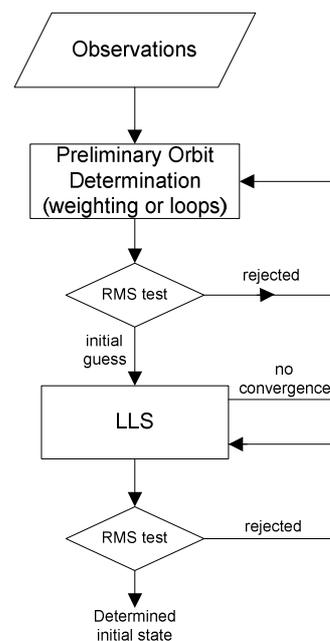


Figure 1. Orbit determination algorithm diagram

If requested, the initial states of a set of VAs are computed along the Line Of Variation (LOV). Finally, the determined initial state of the NEO is used in order to analytically compute its MOID by using the Sitarski method. The vector, identifying the LOV, can be computed from the covariance matrix, corresponding to the LLS solution, by using the first or the second eigenvalue (depending on the user settings). Each VA is computed from the previous one by moving along the LOV. An iterative technique is used to assure that the new VA belongs to the LOV, whose direction vector is indeed recomputed constantly to improve the convergence.

In this new version of the tool, it is possible also to perform orbit determination and trajectory propagation of comets. For this purpose solar radiation pressure and outgassing perturbation have been added and taken into account in the orbital propagators (analytical and numerical).

3. NUMERICAL MODULE

3.1. Propagator

The Numerical Module performs numerical integrations. When the MOID computed by the Analytical Module is small enough to be potentially dangerous for the Earth (e.g. smaller than 0.005 AU), a numerical integration is recommended.

This module can be run for a ‘fast analysis’, which uses a reduced set of models (and already pre-customized), and for a ‘complete analysis’, which allows the user to further customize the propagator using more complex models. For both analyses the user can select one of the following integrators: Runge-Kutta 4, Runge-Kutta 4 adapted, Runge-Kutta 45, Runge-Kutta 853, Dormand-Prince 8, Gauss-Jackson 8, Gauss-Jackson 8 adapted and Gauss-Jackson 8 self-adapted. The term “adapted” has been used to distinguish the original integrator scheme from a new algorithm implemented in NEOProp to improve the performance. The “adapted” integrators are fixed step-size integrators which are able to reduce the step-size whenever a certain condition applies: the NEO exits the sphere of influence of the Sun (adapted) or the ratio between the acceleration due to perturbations and the total acceleration is larger than 0.0001 (self-adapted).

The available perturbation models for each type of analysis are listed in Table 1.

Table 1. Available perturbation models

“Fast” Analysis	“Complete” Analysis
Third-Body (planets)	Third-Body (planets + 4 main asteroids)
-	Relativistic Effects
Solar Radiation Pressure	Solar Radiation Pressure
-	Yarkovsky
Earth Spherical Harmonics	Earth Spherical Harmonics
-	*Poynting Robertson drag
-	*Sun J2
*Outgassing	*Outgassing

*new in NEOProp2

3.2. Risk Assessment

Orbit determination algorithms are limited by finite precision in positional measurements and finite lengths of measured orbital arcs, there are natural uncertainties associated with close approach predictions. When a NEO is recognized to have a future close approach to Earth and has an orbital position uncertainty that intersects the known location of the Earth on a specific date, a collision probability can be calculated.

An object's orbit is never known exactly because the orbit calculation is based on measurements which always contain small errors. The level of uncertainty in an orbit is quantified by the orbital covariance matrix, which depends on several factors:

- time span of the observational arc;
- number, type and accuracy of the observations;
- object's distance from the Earth when observed.

In the prediction of close approaches of NEOs it is important to consider their uncertainties, which can be quite large. In particular, the impact probability P is a function of the position and velocity uncertainties during the encounter.

A straightforward method for computing the impact probability is simply to count the number of virtual asteroid with a minimum close approach distance within one planetary radius. This is computationally expensive because many samples are required in order to identify very low impact probabilities: if the impact probability is of the order of $1E-x$, more than $1E+x$ VA are required to find a virtual Impactor (1 million VA to assess $1E-6$ impact probability).

To reduce the necessary number of simulations, a statistical approximation can be adopted. If the PDF is Gaussian and if the expression is converted into spherical coordinates, the following relation provides the impact probability P [2]:

$$P = \int_0^{r_E} PDF(r)dr = CDF(r_E) - CDF(0) = \frac{\left[\operatorname{erf}\left(\frac{r_E - d}{\sigma\sqrt{2}}\right) - \operatorname{erf}\left(\frac{-d}{\sigma\sqrt{2}}\right) \right]}{2} \quad (1)$$

where CDF denotes the cumulative density function, d is the mean distance from the Earth, σ is the standard deviation of the perigee distances from the Earth, r is the heliocentric position vector and r_E is the radius of the Earth.

Once the impact probability has been computed, the typical hazard scales used by the scientific community can be used to assess the impact risk:

- Torino scale, which is a 0-10 scale that takes into consideration multiple aspects as the impact probability and the kinetic energy of the object, the potential consequences should an impact occur, the time horizon for forecasting all potential impacts, and conveyance as to whether the specific threat posed is significantly higher or lower than that posed by the multitude of similar-sized objects that remain undiscovered [3]2. Unfortunately it tends to deemphasize the threat posed by very large impacts, while it raises smaller impacts to a level of concern that is perhaps more than necessary based on the potential threat alone.
- Palermo scale, which tries to correct some limitations of the Torino scale, taking into consideration the time remaining until the foreseen impact, which is also a way to express how pressing and sure is a certain event [4].

Another important new feature of the Numerical Module is the backwards propagation. In the previous version of the tool only forwards propagation was supported. This new functionality could be used for several purposes as recovery of lost objects, identification of NEOs, etc.

4. GRAPHICAL USER INTERFACE

The GUI developed for NEOProp2 does not add any new functionality to the software, but it tries to simplify and improve the usability of the tool. In this chapter its main features are presented.

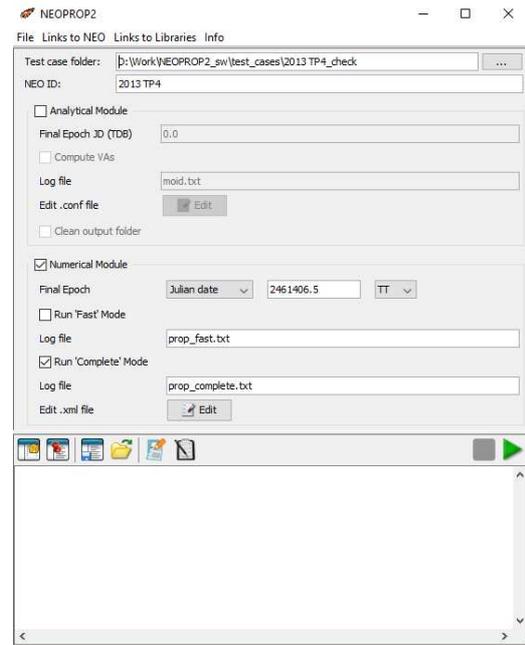


Figure 2. NEOProp2 GUI screenshot

The 'File' menu allows the user to create a new scenario, load an existing one, reload, save or create a backup copy of the current scenario.

The creation and execution of a new scenario are always delicate tasks if performed with software which does not provide a GUI. Especially for new users, retrieving the correct list of input files and data and understanding how to correctly setup the tool can be quite challenging. For this purpose this GUI provides a dedicated panel (see Figure 3) where a new scenario can be created, allowing the user to collect with few clicks all the inputs required to set up a new test case. All the requested input files are automatically created. Not all the input settings stored in the configuration files can be modified from the GUI, but the most common applications should be able to run successfully with the default values.

Once the 'Create' button in the 'New Scenario' dialog panel is pressed, a new scenario is created: a new folder with the provided name is generated and placed at the specified location. If the 'Download observations from MPC' checkbox is selected, the tool tries to download the observation file from the MPC website, using the provided identifier, which therefore needs to be consistent with the one used by the MPC website. The diameter of the NEO can be also retrieved from internet and used to estimate its mass. Alternatively, the user can provide numerical values.

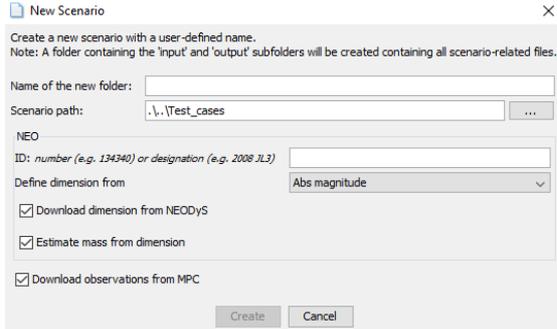


Figure 3. GUI dialog panel for the creation of a new scenario

Once a scenario has been created or loaded, the user can access some useful internet links to the MPC, JPL, ESA SSA, NEODYs and Sentry pages through the ‘Links to NEO’ menu. Moreover, links for the selected NEO to the NEODYs and Sentry pages are available. If the NEO is inserted in the risk list, links to the NEODYs and Sentry risk pages are accessible too, instead of being greyed out. Some useful internet links are provided also in the ‘Links to Libraries’ menu. From there, the user can open internet pages where most of the NEOProp2 libraries are taken from.

The configuration panel allows the user to modify some of the settings of the current scenario. In this panel the user can select also which modules have to be run.

The toolbar allows the user to run (and stop) any NEOProp2 module, to create a scenario summary or results comparison and also to save or load the content of the log pane, which visualizes in real time the output stream of a running executable. In this way the user is informed about the current status of a certain action/analysis. The log pane is also used to visualize (in html format) the scenario report and results comparison.

Users can generate a scenario summary and/or compare the results obtained by NEOProp2 with the values reported by NEODYs and Sentry. In both cases results are separated in three sections, one per task (Analytical Module, Numerical Module fast and complete).

The scenario summary functionality collects all the information from the output files stored in the output folder and writes them into the log pane. In this way the user gets a rapid overview of the results without the need of accessing manually all the files. Orbital elements, MOID, close approaches, Earth virtual impactors and risk figures are reported.

5. RESULTS

In order to verify the software requirements and to validate the tool, the original functionalities implemented in NEOProp had to be retested. Therefore,

all the test cases already used to test NEOProp (and presented in [1]) have been re-run and the results successfully crosschecked. Additionally, new test cases were defined in order to verify whether the new functionalities introduced in NEOProp2 work correctly. Only these new test cases are presented in this chapter.

5.1. Analytical Module Improved Convergence

In the previous version of the tool, sometimes, especially when dealing with long observational arcs, the set of observations had to be split in order to make the LLS converge. The new algorithms implemented in NEOProp2 should be able to overcome this issue. To verify the new implementation, all the NEOs, which required splitting the observational arc [1], were again analysed and tested with the whole observational arc at once. The identified NEOs are: Apophis, 2004DC and 2012DA14. This last NEO is of particular interest since it required a three-step orbital fit, due to a close approach that this NEO had with the Earth. NEOProp2 successfully managed to perform orbit determination in a unique shot and the obtained orbital elements were in line with the reference (NEODYs) and reported below.

Table 2. NEODYs-NEOProp2 results comparison (99942, 2009FJ, 2011AG5)

	99942	2009FJ	2011AG5
Epoch [JD]	2456400.5	2456200.5	2456400.5
Δ-a [AU]	3.5950E-09	-0.00046	1.19E-08
%-a	0.000%	-0.021%	0.000%
Δ-e [-]	-2.8690E-09	-9.2E-05	2.54E-08
%-e	0.000%	-0.016%	0.000%
Δ-i [°]	1.7410E-08	-0.00182	0.001224
%-i	0.000%	-0.206%	0.033%
Δ-Ω [°]	-1.9900E-07	-0.01126	0.018876
%-Ω	0.000%	-0.003%	0.014%
Δ-ω [°]	-4.2500E-07	0.011993	-0.01893
%-ω	0.000%	0.008%	-0.035%
Δ-M [°]	6.2300E-07	0.123461	2.1E-06
%-M	0.000%	0.339%	0.000%
Δ-MOID [AU]	0.000%	3.8E-07	-3.8E-06
%-MOID	0.000%	0.030%	-1.042%

5.2. Comet Orbit Determination and Propagation

NEOProp2 is now able to identify and propagate orbits of comets, while NEOProp could analyse only NEOs. In order to validate this functionality, the new algorithms for orbit determination and trajectory propagation were tested with two comets: 319P/Catalina-McNaught and 67P/Churyumov-Gerasimenko. These comets have been

selected because they provide not only the possibility to test the orbit determination module, but also the numerical one, since they both present close approaches to at least one of the planets. Their reference values have been taken from the Sentry system since NEODYs does not consider comets at the moment.

Comet 67P is of particular interest since it is the comet targeted by the Rosetta mission. It also gives the possibility to test the implementation of the outgassing perturbation, since the required input coefficients for the outgassing model are available for this comet and have been published by Sentry.

The analytical and numerical modules have been both run, once including the outgassing perturbation and once without it. The orbit determination produced almost the same values in both cases. Therefore, only the results obtained considering the outgassing perturbation are presented in Table 3. The determined orbital elements are very close to the reference ones, except for the mean anomaly, since the reference orbital elements were available at a different epoch (7 years later) from the one computed by NEOProp2. Nevertheless, the computed analytical MOID is almost identical to its reference value.

Table 3. NEOProp2 results and comparison with Sentry for comet 67P

	NEOProp2	Difference
<i>Epoch [JD]</i>	2454642.574744	-2619.92526
Δ -a [AU]	3.466402	0.13%
Δ -e [-]	0.640288	-0.09%
Δ -i [°]	7.041595	0.02%
Δ - Ω [°]	50.210012	0.15%
Δ - ω [°]	12.652102	-1.13%
Δ -M [°]	322.087716	-1761.42%
Δ -MOID [AU]	0.2610731909	1.11%

On the other hand, the effect of the outgassing perturbation plays a big role in the long term trajectory propagation. In the next table the close approach to Mars, that will take place in 2067, has been compared once with the results obtained without considering the outgassing perturbation (first row) and once with the results computed including that effect. From the numerical values, the benefit due to the use of the outgassing force is obvious.

Table 4. 67P Close approach comparison with Sentry with and without considering outgassing

#	Δ -Date	Distance %
1 (no outgassing)	-0.71693	-6.752%
1	0.03307	-0.001%

The 319P comet could not be tested with the outgassing perturbation, since it was not possible to find the numerical values for its coefficients. Nevertheless, the computed orbital elements and MOID are very close to the reference values (considering again the different reference epoch).

Table 5. NEOProp2 results and comparison with Sentry for comet 319P

	NEOProp2	Difference
<i>Epoch [JD]</i>	3.568053	-0.10%
Δ -a [AU]	0.666418	0.18%
Δ -e [-]	15.101114	0.15%
Δ -i [°]	111.386396	0.01%
Δ - Ω [°]	203.635114	-0.04%
Δ - ω [°]	358.049192	77.39%
Δ -M [°]	2454727.989414	1394.51059 [d]
Δ -MOID [AU]	0.1943621846	-2.40%

This comet is also very interesting due to the two close approaches to the Earth. Both of them have been successfully identified by NEOProp2.

Table 6. 319P Close approach comparison with Sentry

#	Δ -Date	Distance %
1	-0.01059	-0.021%
2	0.03108	0.09%

5.3. NEOs Risk Assessment

The last test was intended to validate the accuracy of the new impact risk assessment computation. NEOProp2 is now able to estimate the impact probability, which can be used then to compute the Torino and Palermo scale values. Three NEOs (2007 SN6, 2012 VE77 and 2013 TP4) having an impact probability non-zero were fully analyzed and their observations used to feed the orbit determination module. The obtained nominal initial states and VAs were used to estimate the impact probability and assess the impact risk. For each NEO, orbital elements, analytical MOID, virtual Earth impactors and Palermo scale values were compared. Torino scale values could not be compared since no NEO having a value above 0 has been discovered yet. Table 7 shows that the orbital elements found by NEOProp2 are perfectly in line with the NEODYs and Sentry values. MOIDs computed by NEOProp2 are very close to the values provided by Sentry, which quite differ from those provided by NEODYs.

Table 7. NEO orbits and MOIDs comparison between NEOProp2 and NEODYs-Sentry

	2007 SN6 NEODYs	2007 SN6 Sentry	2012 VE77 NEODYs	2012 VE77 Sentry	2013 TP4 NEODYs	2013 TP4 Sentry
<i>Epoch [JD]</i>	0.35	-0.07	-0.11	-0.13	-2.10	-4.56
Δ -a [AU]	0.00%	0.00%	-0.03%	0.04%	0.09%	0.02%
Δ -e [-]	0.00%	0.00%	-0.03%	0.04%	0.04%	0.00%
Δ -i [°]	0.00%	0.02%	-0.02%	0.00%	0.03%	-0.02%
Δ - Ω [°]	0.00%	0.00%	-0.02%	0.00%	0.04%	0.00%
Δ - ω [°]	0.02%	0.00%	-0.06%	-0.01%	0.01%	0.00%
Δ -M [°]	0.03%	-0.16%	-0.06%	-0.01%	-0.29%	-8.58%
Δ -MOID	94.598%	0.00%	28.915%	0.06%	-12.143%	0.275%

In Table 8 the Earth virtual impactors reported by NEODYs and Sentry are compared with those computed by NEOProp2. The comparison shows that NEOProp2 results are closer to Sentry's values for the 2007 SN6 NEO, closer to NEODYs for the 2012 VE77 asteroid and close to both of them (since they are in agreement) for the last asteroid. This result shows that NEOProp2 is independent from both these systems, which was one of the fundamental software requirements in order to make of NEOProp2 an independent benchmarking tool for these existing systems.

The computed impact probabilities are not always very close to the reference values, but as mentioned in [5] differences up to one order of magnitude are considered fully acceptable.

Table 8. Earth virtual impactors' comparison between NEOProp2 and NEODYs-Sentry

NEO	NEODYs			Sentry		
	Δ -Date [d]	Δ -Impact prob. [-]	Δ -Palermo [-]	Δ -Date [d]	Δ -Impact prob. [-]	Δ -Palermo [-]
2007 SN6	0.00715	5.376E-06	1.552	-	-	-
	-	-	-	-	-	-
2012 VE77	0.03477	-2.9E-05	-0.53	0.03546	-7.03E-05	-0.9
	-	-	-	0.03378	7.9E-06	0.684
2013 TP4	0.03089	1.53E-05	0.202	0.03089	2.58E-05	0.312

6. CONCLUSIONS

NEOProp2 is not only an upgraded and overall improved version of NEOProp, but it implements many new features which have widened the capabilities of the tool.

The software is now able to perform orbit determination not only of NEOs, but also of any other celestial body, including comets, due to newly implemented perturbation models (e.g. outgassing force and Poynting-Robertson drag). The determination of virtual asteroids has been greatly improved in terms of accuracy and performance. Multiple definitions of LOV are now supported. Meanwhile, the convergence of the orbit determination algorithm has been improved and an outer loop has been added in order to increase the robustness of the Analytical Module.

The Numerical Module also supports the propagation of comets. Moreover, the computational time and the consumption of memory have been reduced. The tool can now assess the impact risks of any object through the computation of important figures as impact probability, Torino and Palermo scale values. Amongst the new features, the backward propagation allows now to use the software not only for risk assessment, but also for other important tasks as object recovery, identification and definition of follow-up observations campaigns.

No big limitation/problems have been identified during the tests, which were also presented in this paper, and the software seems to be flexible (able to tackle objects of various types and with very different orbital elements) and good performing. So far only a system engineering validation and verification could be performed, an extended testing campaign is recommended to really understand potentialities and limitations of the tool.

NEOProp has been thoroughly reviewed and improved and the new NEOProp2 has been shown/proved to be both more robust and faster than its predecessor. The newly developed GUI facilitates the user experience, allowing to easily create and run a new scenario and to compare the results with the other available prediction tools.

7. REFERENCES

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