

NEOPROP2

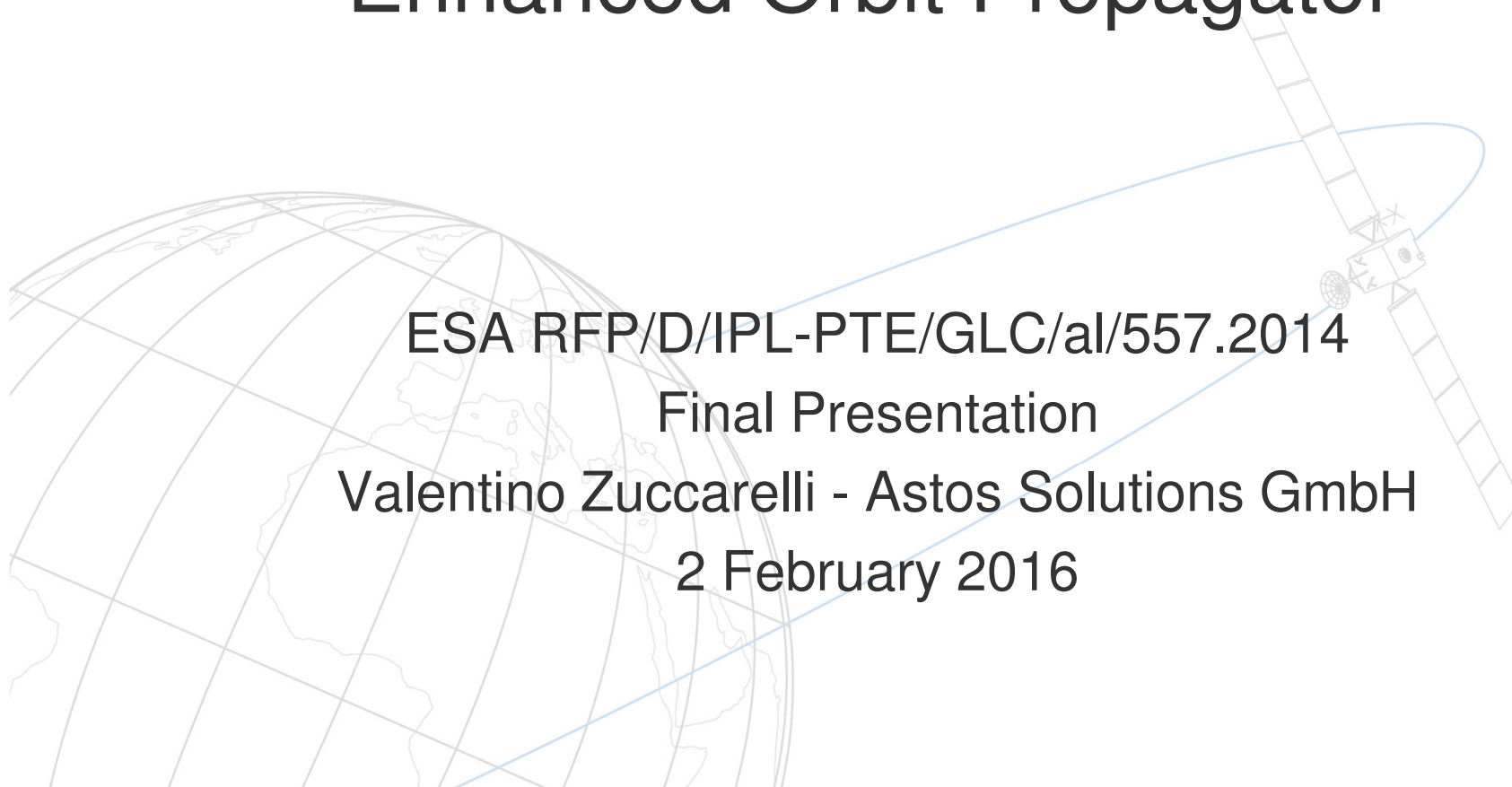
Enhanced Orbit Propagator

ESA RFP/D/IPL-PTE/GLC/a/557.2014

Final Presentation

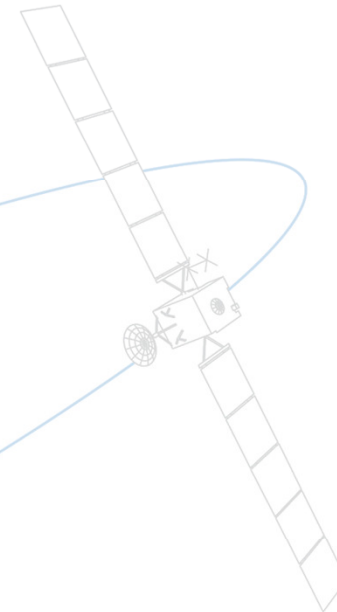
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2 February 2016



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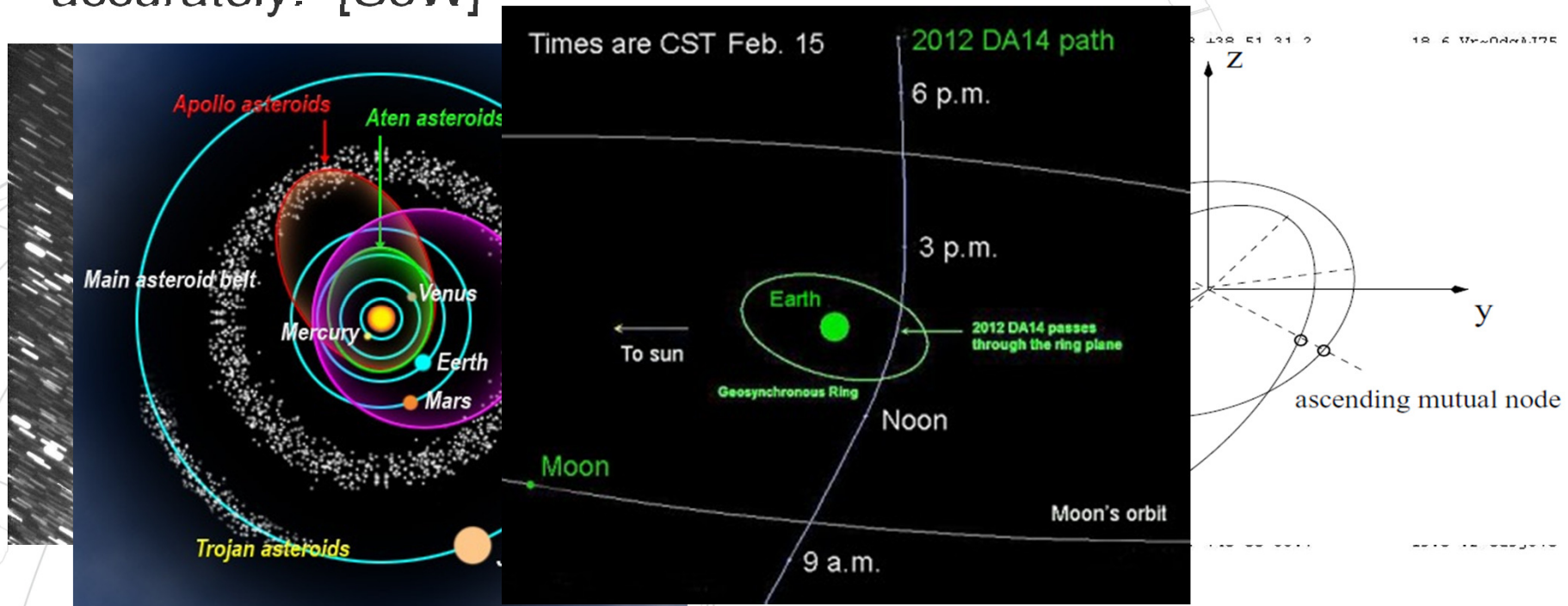


History

- November 2010, SoW (ESTEC 1-6657/10/NL/MH/ps) was released, requesting a trajectory prediction algorithm including:
 - Orbit determination
 - Trajectory propagator
 - Computation of MOID (Minimum Orbital Intersection Distances)
- 2011-2013 Astos Solutions in collaboration with IMCCE developed NEOPROP
- March 2014, SoW (ESA RFP/D/IPL-PTE/GLC/al/557.2014) was released, requesting:
 - Enhanced algorithms
 - Impact risk assessment
- 2014-2015 Astos Solutions developed NEOPROP2

NEOPROP Objective

“The key objective of this activity is to design, develop, test, verify and validate trajectory prediction algorithm of NEOs. The final objective of these new prediction algorithms shall be to compute minimum orbital intersection distances (MOIDs) accurately.” [SoW]



NEOPROP Requirements

Functional Requirements

The tool shall allow:

- Orbit determination
- Estimation of the uncertainties
- Numerical orbit propagation
- MOID computation

Design Requirement and Implementation Constraint

The tool shall implement, whenever possible, different algorithms from those used in NEODyS.

NEOPROP Architecture

Two separate modules/tools:

1. The **Analytical Module** rapidly assesses the impact risk of a NEO. An Orbit Determination (OD) algorithm will determine the initial state of the NEO, which is used to compute the MOID.

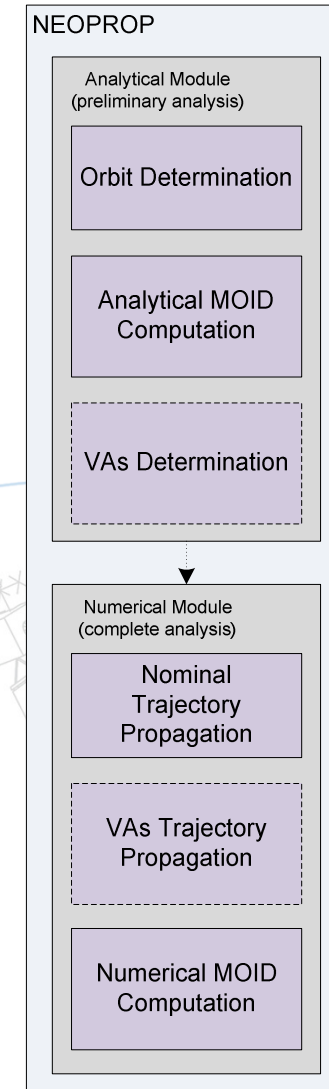
A set of VAs can be computed along the LOV.

2. The **Numerical Module** refines the risk assessment (if required). The initial state provided by the OD process will be numerically propagated. The numerical propagation can be run in two modes:

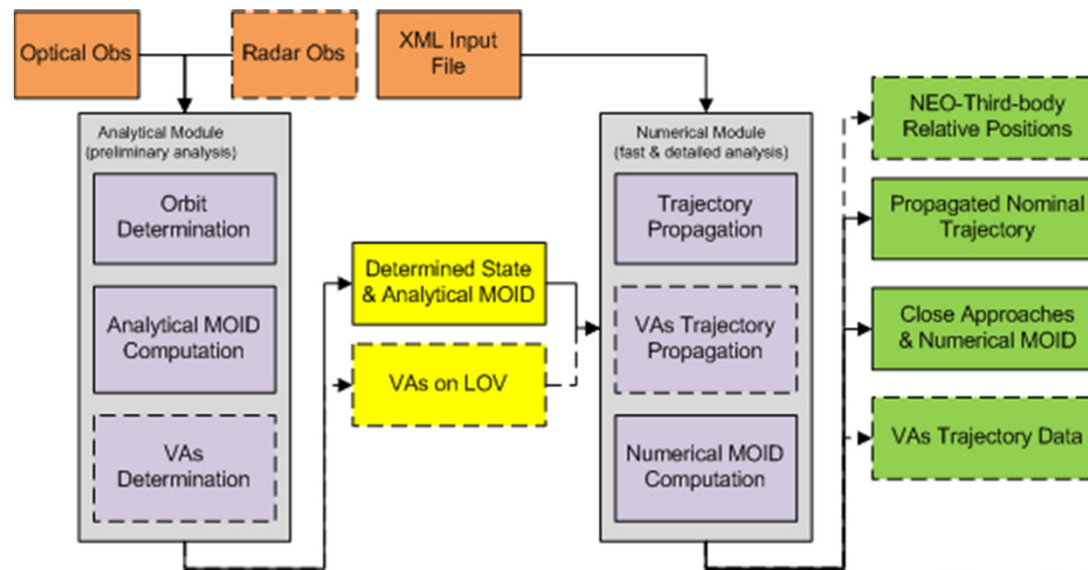
- fast propagation (simplified models)
- more precise propagation (complete models)

Also the dynamical MOID will be computed.

A set of VAs can be propagated.



NEOPROP Interfaces



The Analytical Module needs as input:

- all the relevant observations

The Numerical Module needs as input:

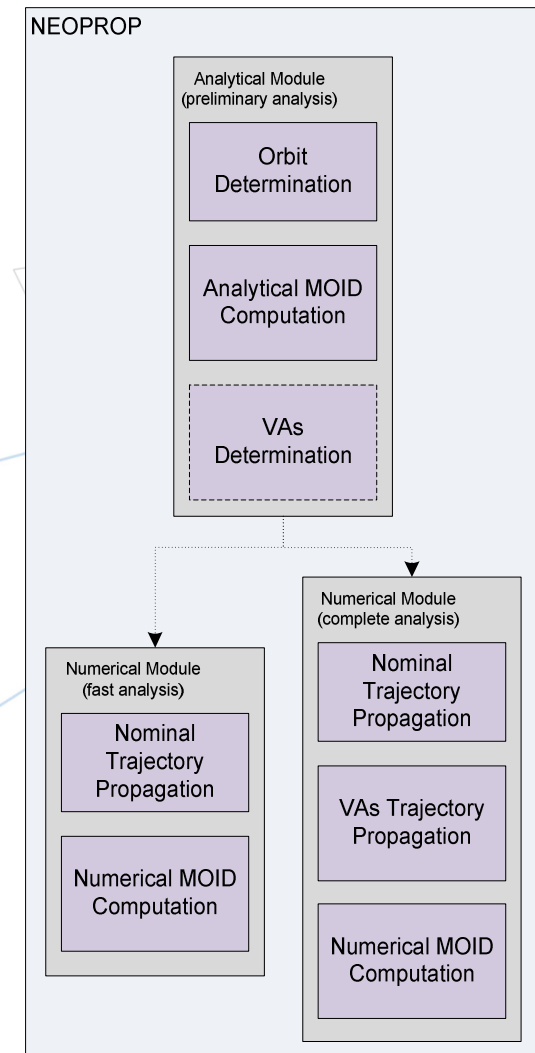
- XML file
- initial state of the NEO (created by the Analytical Module)
- initial states of the VAs (optional)

NEOPROP Modes

The SW can be run in three different modes:

1. Preliminary Analysis
2. Fast Analysis
3. Complete Analysis

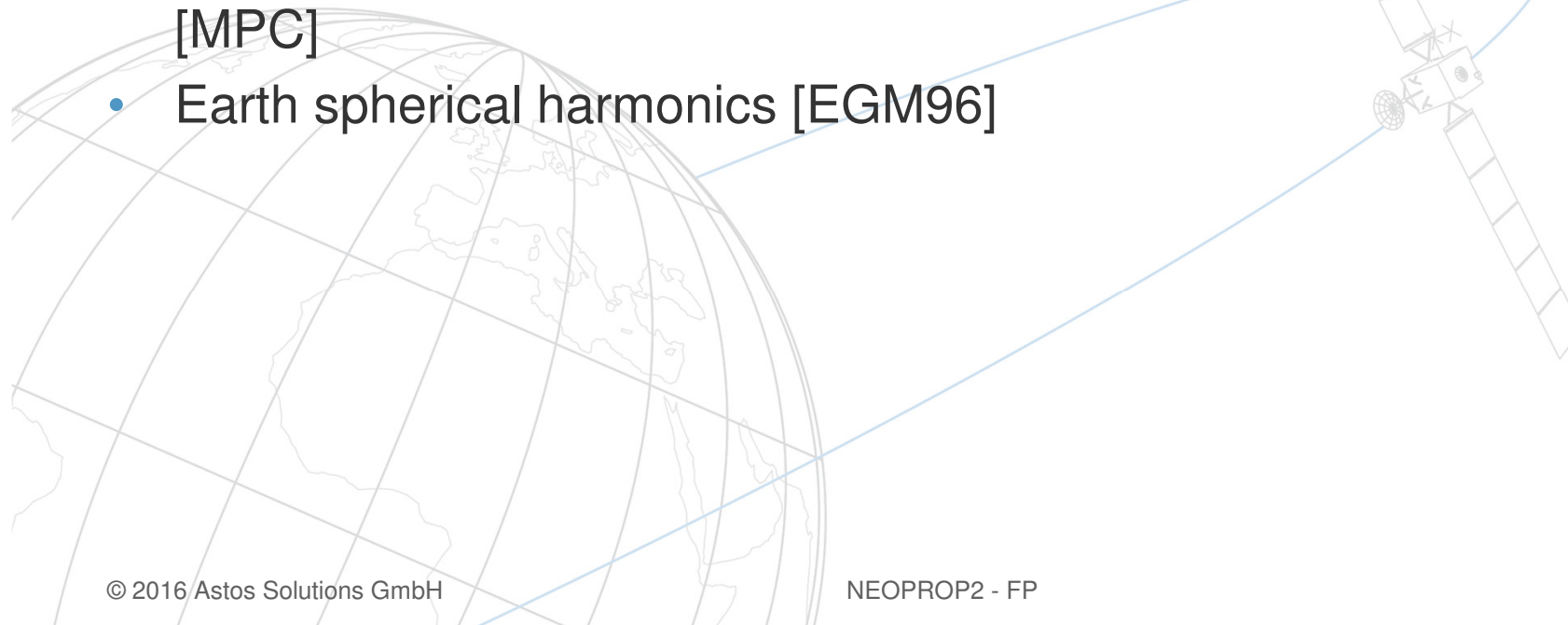
Mode	Executable	Analysis/Task
1	<i>NEOPROP_MOID</i>	Orbit determination Computation of the analytical MOID
2	<i>NEOPROP_MOID</i> <i>NEOPROP_prop_fast</i>	Orbit determination Computation of the analytical MOID Trajectory propagation of the initial state Computation of the numerical MOID and close approaches
3	<i>NEOPROP_MOID</i> <i>NEOPROP_prop_complete</i>	Orbit determination Computation of the analytical MOID Computation of the VAs along LOV Trajectory propagation of the initial state Computation of the numerical MOID and close approaches Trajectory propagation of VAs



NEOPROP External Libraries

The following external libraries/database are used in NEOPROP:

- Spice ephemeris [JPL]
- Asteroid orbits database [Astorb]
- Time standards conversion tables (TAI-UTC, TT-UT1) [IERS]
- Earth orientation data [IERS]
- Observatories database (including accuracy of their observations) [MPC]
- Earth spherical harmonics [EGM96]



Test Campaign Results (1/2)

- TC-0020: Apophis orbit determination
- States (with uncertainties) and MOID compared to NEODyS

	NEODyS	NEOPROP	Δ -Value	%-Value
a [AU]	9.2209E-01	9.2209E-01	1.6672E-09	0.00%
e [-]	1.9116E-01	1.9116E-01	-1.3236E-08	0.00%
i [°]	3.3306E+00	3.3290E+00	1.5788E-03	0.05%
Ω [°]	2.0422E+02	2.0424E+02	-1.2200E-02	-0.01%
ω [°]	1.2646E+02	1.2644E+02	1.2229E-02	0.01%
M [°]	2.3547E+02	2.3547E+02	-2.5629E-05	0.00%
a 1-σ [AU]	5.4250E-10	5.4568E-10	-3.1804E-12	-0.59%
e 1-σ [-]	1.7320E-08	1.7347E-08	-2.6598E-11	-0.15%
i 1-σ [°]	8.3860E-07	8.4076E-07	-2.1600E-09	-0.26%
Ω 1-σ [°]	2.8140E-05	2.8325E-05	-1.8489E-07	-0.66%
ω 1-σ [°]	2.8610E-05	2.8798E-05	-1.8833E-07	-0.66%
M 1-σ [°]	6.5450E-06	6.5623E-06	-1.7274E-08	-0.26%
MOID [AU]	2.4931E-04	2.4931E-04	-1.0043E-08	0.00%

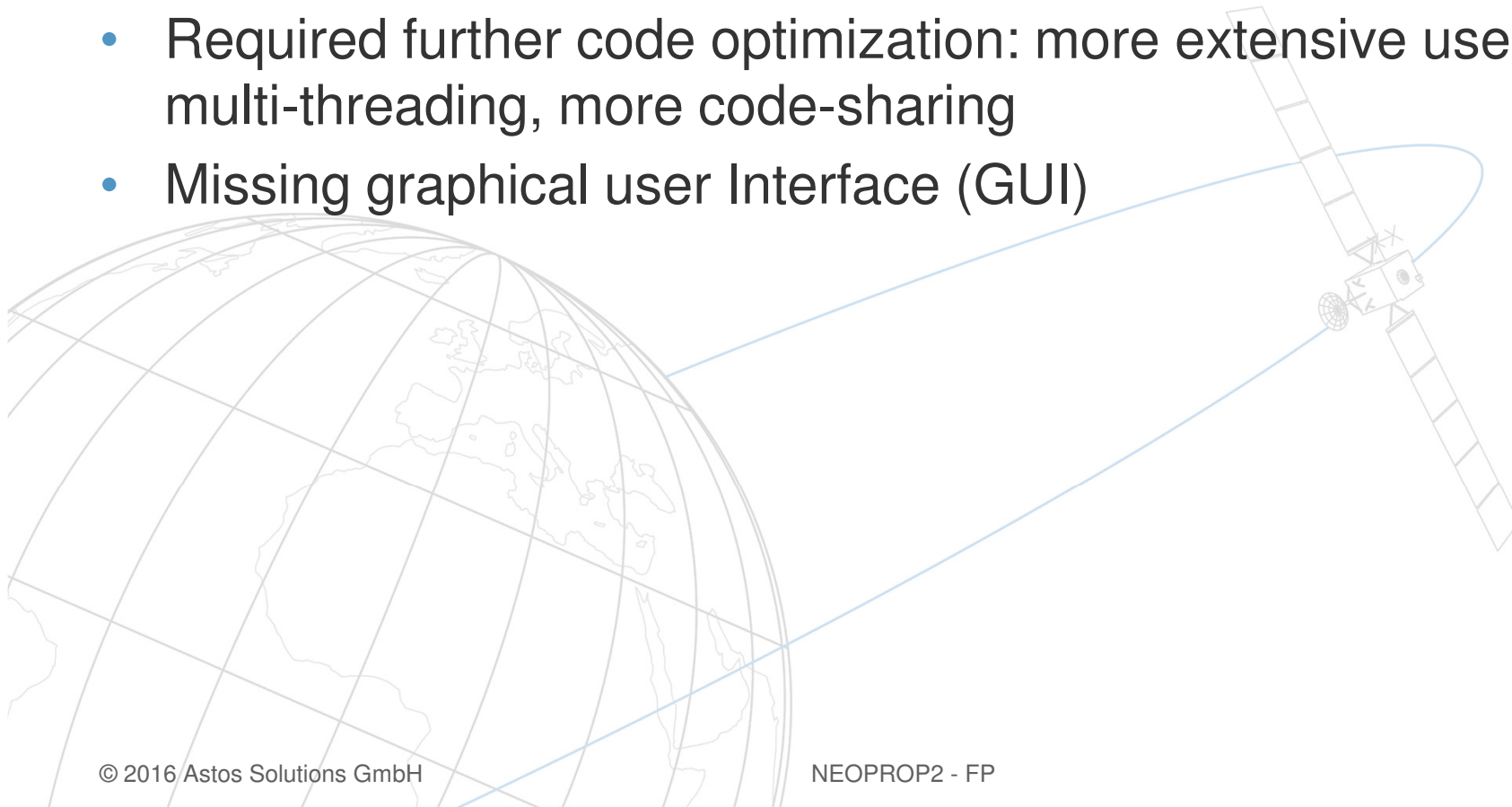
Test Campaign Results (2/2)

- TC-0030: Apophis numerical trajectory propagation
- Earth and Moon close approach distances (2029-04-13/14) compared to: JPL-Horizons and “Predicting the Earth encounters of (99942) Apophis” [Giorgini et al.]
- Simulated 3 different set of physical parameters

	x [km]	y [km]	z [km]	Vx [km/s]	Vy [km/s]	Vz [km/s]	MOID Earth [AU]	MOID Moon [AU]
Horizons	-1.325E+08	-6.199E+07	-2.650E+07	1.856E+01	-2.361E+01	-8.929E+00	2.562E-04	6.363E-04
NEOPROP Ref	-1.325E+08	-6.199E+07	-2.651E+07	1.857E+01	-2.361E+01	-8.957E+00	2.537E-04	6.391E-04
Δ-Value	-3.194E+03	1.862E+03	7.585E+03	-9.516E-03	5.233E-03	2.844E-02	2.540E-06	-2.871E-06
%-Value	0.00%	0.00%	-0.03%	-0.05%	-0.02%	-0.32%	0.99%	-0.45%
NEOPROP min	-1.325E+08	-6.199E+07	-2.651E+07	1.857E+01	-2.361E+01	-8.950E+00	2.548E-04	6.362E-04
Δ-Value	-2.139E+03	-4.366E+01	5.573E+03	-6.309E-03	-1.278E-03	2.121E-02	1.366E-06	8.743E-08
%-Value	0.00%	0.00%	-0.02%	-0.03%	0.01%	-0.24%	0.53%	0.01%
NEOPROP max	-1.325E+08	-6.199E+07	-2.651E+07	1.857E+01	-2.361E+01	-8.954E+00	2.542E-04	6.377E-04
Δ-Value	-2.687E+03	9.451E+02	6.616E+03	-7.974E-03	2.100E-03	2.496E-02	1.976E-06	-1.444E-06
%-Value	0.00%	0.00%	-0.02%	-0.04%	-0.01%	-0.28%	0.77%	-0.23%

NEOPROP Limitations

- Bad convergence with long and/or discontinuous observational arcs
- Missing computation of the impact probability
- Required further code optimization: more extensive use of multi-threading, more code-sharing
- Missing graphical user Interface (GUI)



NEOPROP2 Requested Features

“The objective of this activity is to enhance the NEOPROP software toolbox with a series of required improvements:”

- Impact probability assessment as Torino scale and Palermo scale values
- Automatic split of the observations into arcs in order to improve the convergence of the orbit determination module
- Poynting-Robertson perturbation (for the numerical propagator)
- NEOPROP's restriction to work with NEOs (pericenter smaller than 1.3 AU), comets could not be analyzed

Risk Assessment: Impact Probability

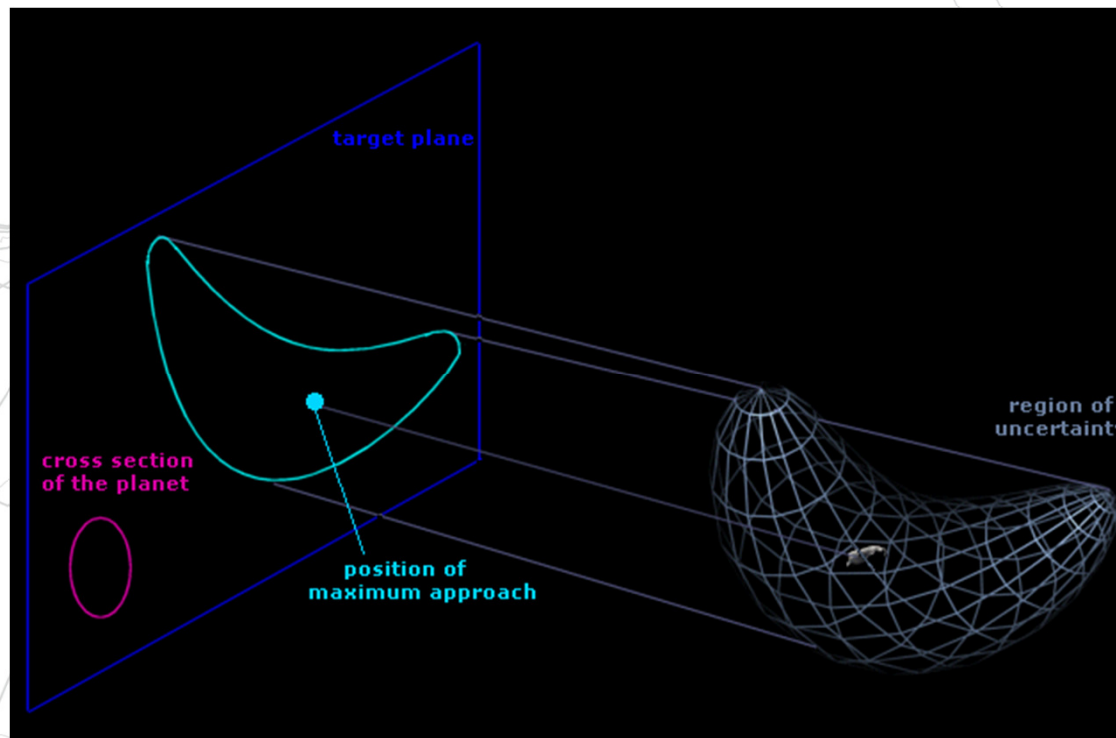
The impact probability P_i needs to be computed in order to obtain Torino and Palermo scale values. It is a function of the position and velocity uncertainties during the encounter, which depend on:

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



Risk Assessment: Linear analysis

The integration of the variational equations allow to compute the state transition matrix, which 'linearly' map the orbital uncertainty at different epochs.



Risk Assessment: Non-linear analysis

Expensive Monte Carlo method: if the impact probability is of the order of $10E-x$, more than $10E+x$ VA are required to find a virtual Impactor (1 million VA to assess $1E-6$ impact probability):

$$P_i = \frac{n_I}{n_{VA}}$$

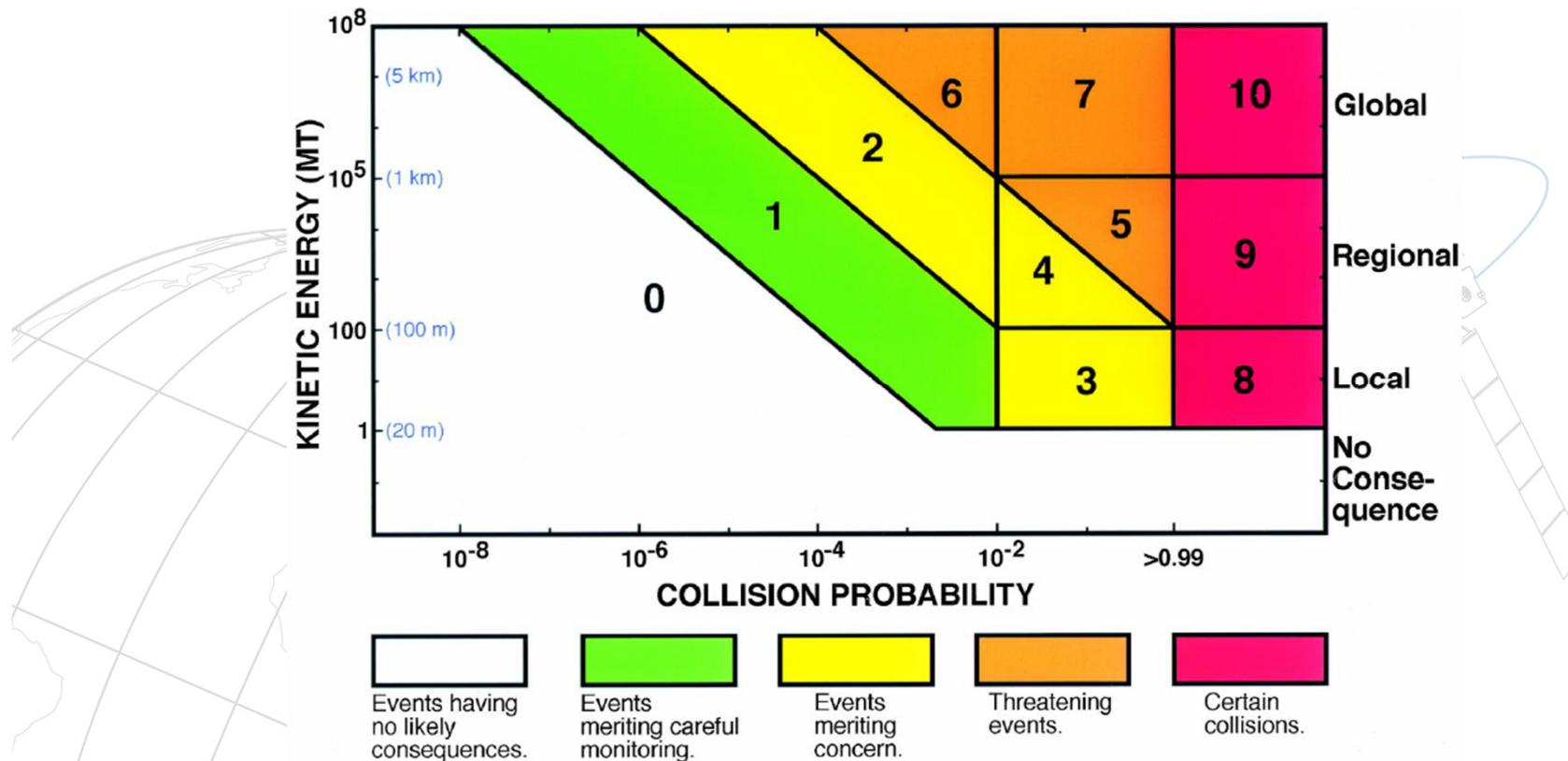
If we assume a Gaussian PDF, P_i becomes:

$$P_i = \int_0^{r_{\oplus}} PDF(r) dr = CDF(r_{\oplus}) - CDF(0) = \frac{1}{2} \left[\operatorname{erf} \left(\frac{r_{\oplus} - \bar{d}}{\sigma\sqrt{2}} \right) - \operatorname{erf} \left(\frac{-\bar{d}}{\sigma\sqrt{2}} \right) \right]$$

Assumption tested on Apophis: $4.2E-6$ vs $4.3E-6$ (ref.) obtained with 1000 VA.

Risk Assessment: Torino Scale

This scale takes into consideration the impact, the kinetic energy, the potential consequences should an impact occur and the time horizon for forecasting all potential impacts.



Risk Assessment: Palermo Scale

Torino Scale 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. Moreover, it does not take into considerations the time remaining until the foreseen impact.

$$P = \log_{10} R = \log_{10} \frac{P_I}{f_B \Delta T}$$

$$f_B = \frac{3}{100} E^{-\frac{4}{5}} [\text{yr}^{-1}]$$

ΔT is the number of years remaining until the potential impact and E is the kinetic energy.

Improved OD: Convergence problem

- NEOPROP uses a LLS technique for OD, which requires an initial guess and then refines the solution minimizing the RMS.
- If the initial guess is too poor, the LLS method may fail to converge.
- The initial guess is obtained by using the Gauss method, which requires exactly 3 observations.
- In case of long observational arcs (several years) and/or discontinuous arcs (e.g. due to a close-approach), the LLS may fail, due to a bad initial guess.

Improved OD: Algorithms

- ‘Selection’ Algorithm:

Selection of the observations to be used during the preliminary OD algorithm, by means of a weighting scheme as in LLS, based on the rate of the observatory and, additionally, on the time interval between the observations (as in NEODyS).

- ‘Grouping’ Algorithm:

Two-nested-loop-algorithm with the outer loop reducing the whole observational arc (considering ‘time jumps’ and observatories) into a shorter arc used for preliminary OD and then the internal loop splitting the whole arc into shorter ones and feeding sequentially the LLS, able to progressively constraint the solution.

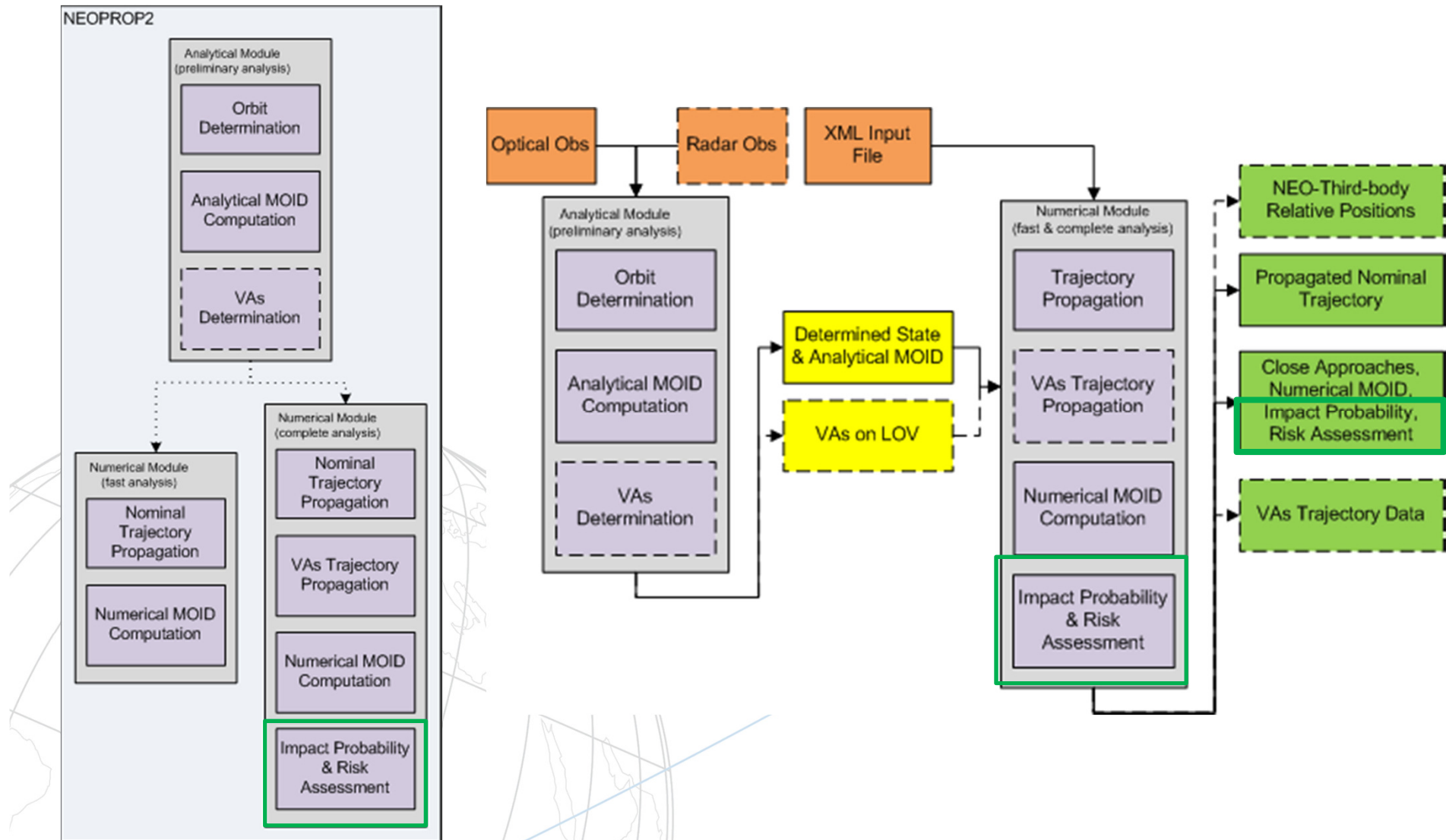
Algorithms Trade-off

Technique	Pros	Cons	Used by NEODyS
Linear Analysis	<ul style="list-style-type: none"> Less VAs required 	<ul style="list-style-type: none"> Single propagation is more complex (6 more equations) Higher implementation effort 	X
Non-linear Analysis	<ul style="list-style-type: none"> Simple implementation No linearization required 	<ul style="list-style-type: none"> Many VAs may be required 	
'Selection' Algorithm	<ul style="list-style-type: none"> May get to the root of the problem Easy to test 	<ul style="list-style-type: none"> Higher implementation effort 	X
'Grouping' Algorithm	<ul style="list-style-type: none"> Simple implementation 	<ul style="list-style-type: none"> Difficult to tune No reference 	<i>manually</i>

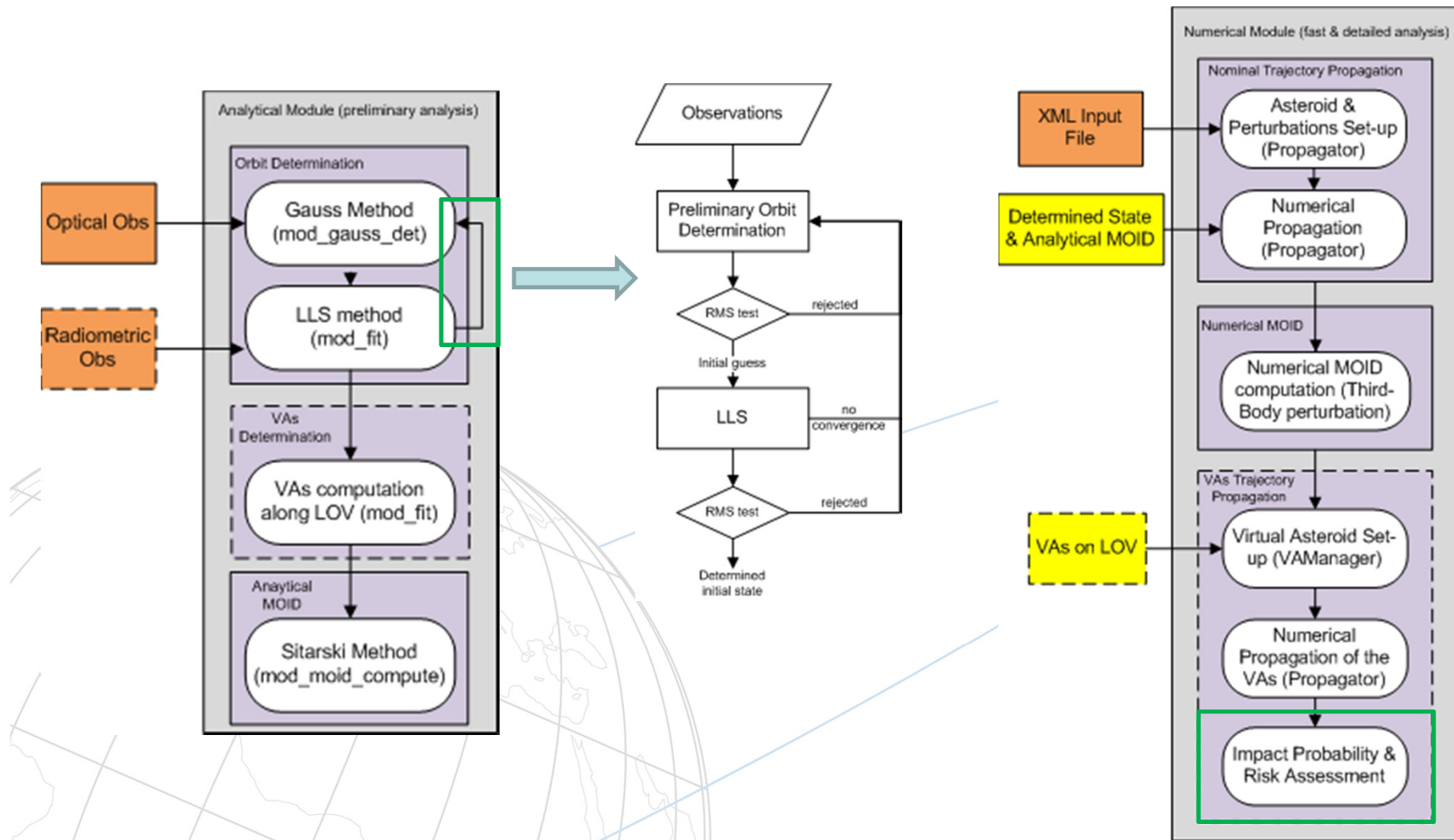
Other improvements

- External libraries maintenance
- Solar radiation pressure for OD
- Implementation of new perturbations:
 - Sun J2
 - Outgassing perturbation (for comets)
 - Poynting-Robertson drag
- New algorithm to compute virtual asteroids along LOV:
 - Improved convergence on the LOV
 - Implemented 4 different LOV definitions (scaled, unscaled, first eigenvalue, second eigenvalue)
- Several bug-fixes
- Code optimization
- GUI

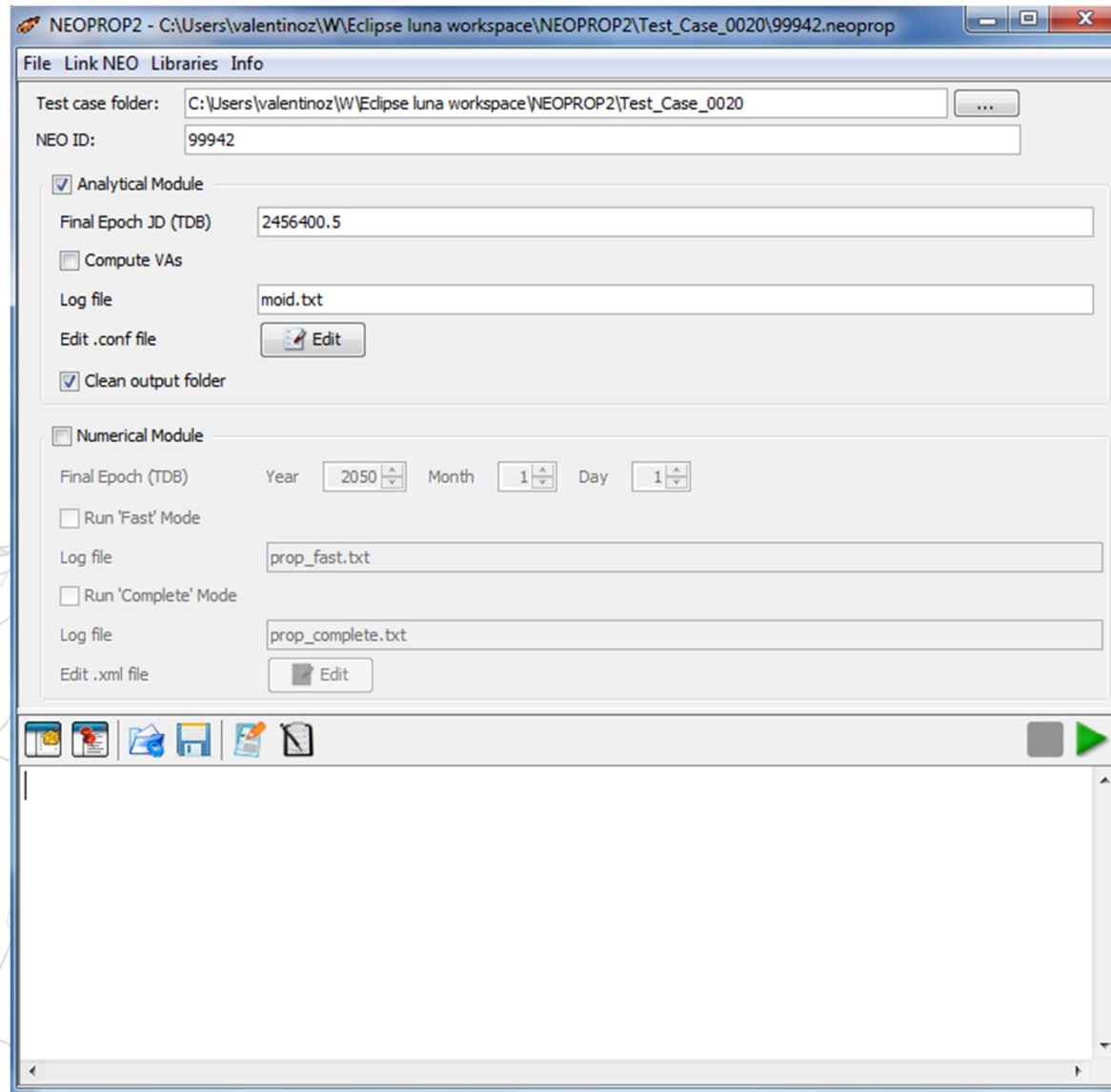
NEOPROP2 Architecture & Interfaces



NEOPROP2 Modules Architecture



GUI: Introduction



← Menu bar

Configuration Panel

← Toolbar

Log Pane

GUI: Menu bar

- **File** allows the user to create a new scenario, load an existing one, reloading or saving the current scenario.
- **Link NEO** provides some internet links to the MPC, JPL, NEODyS and Sentry pages. Links for the current NEO to the NEODyS and Sentry pages are showed. If the NEO is inserted in the risk list, links to the risk pages are showed.
- The **Libraries** menu provides links to the webpages where most of the NEOPROP2 libraries are taken/updated from.
- The **Info** menu contains the link to the SUM and some general information about the tool itself.

GUI: Configuration panel

- It allows to modify settings of the current scenario.
- Values displayed in this panel are used once the 'Run' button is pressed. The 'Save' button stores these values in the .neoprop file.
- It allows to select which executables have to be run.
- Two 'Edit' buttons are available allowing to open the default text editor in order to edit the '.conf' and the '.xml' files.

GUI: Toolbar & Log pane

The toolbar allows to:

- Run ► (and stop ■) any NEOPROP2 executable.
- Create a scenario summary 📄 or results comparison 📊.
- Save 💾 or load 📂 the content of the log pane.

The log pane allows to:

- visualize in real time (text format) the output stream of a running executable.
- to visualize (html format) the scenario report and results comparison.

Test Campaign Results (1/2)

- TCs 0010-0090 checked that NEOPROP2 fullfils the NEOPROP requirements too.
- TC 0060 Software algorithms:

Task	NEOPROP2 algorithm	NEODyS algorithm	Note
Preliminary Orbit Determination	Gauss method	Gauss method (Väisälä & Laplace)	Gauss method by default
Orbital improvement	LLS method	LLS method	-
Analytical MOID computation	Sitarski method	Algebraic method	Same method for the uncertainty
VAs computation	LOV + MC	LOV	Same technique for the the LOV, but added random VAs
Trajectory Propagation	GJ8, RK4, RK853, RK45, DP8	Everhart's Radau Integrator	Same set of perturbations (3rd-bodies, relativistic effects, Yarkovsky, SRP), not always same model
Impact probability	Non-Linear analysis	Linear analysis	-

Test Campaign Results (2/2)

- TC 0100 Orbit Determination Convergence (Apophis, 2004DC and 2012DA14) without splitting the observations
- TC 0110 Comet Orbit Determination & Propagation (319P/Catalina-McNaught and 67P/Churyumov-Gerasimenko)

67P Close-Approach #	Δ -Date	Distance %
1 (no outgassing)	-0.71693	-6.752%
1	0.03307	-0.001%

- TC 0120 NEO Risk Assessment (2007SN6, 2012VE77, 2013TP4)

NEO	NEODyS			Sentry		
	Δ -Date [d]	Δ -Impact probability [-]	Δ -Palermo [-]	Δ -Date [d]	Δ -Impact probability [-]	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

Demo part 1: GUI

1) New scenario creation (2006 DM63 and 2008 HJ):

- Download dimension from NEODyS
- Download observations from MPC

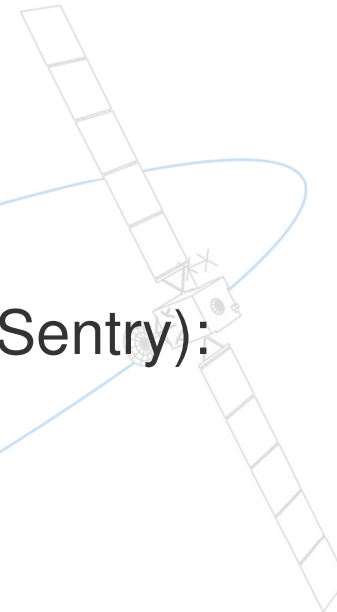
2) Scenario execution:

- Analytical module, only orbit determination
- Fast numerical module, nominal orbit propagation

3) Scenario summary

4) Scenario results comparison (NEODyS & Sentry):

- Orbital elements
- Close approaches (until 2050 and below 0.05 AU)



Demo part 2: Comet & Risk Assessment

Comet:

- 1) (Iterative) orbit determination of a comet (P/2008 S1)
- 2) Numerical trajectory propagation
- 3) Close approaches (until 2036 and below 0.21 AU)

Risk assessment:

- 1) Orbit determination and VAs precomputed (2013 TP4)
- 2) Nominal and VAs trajectories prepropagated
- 3) Risk assessment precomputed (until 2027 and below 0.005 AU)
- 4) Scenario results comparison

Leadership requires solutions



Thank you!

