EXECUTIVE SUMMARY

SGNEOP

Synthetic Generation
of a NEO Population

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1 Introduction

1.1 Scope of this Document

This document is intended to give readers a general overview of project SGNEOP and its outcomes. It gives readers a basic insight into the project; for detailed information, the Final Report [07] should be consulted.

1.2 Project Overview

Objects whose orbits are in vicinity to Earth's orbit bear the risk of an impact harming habitants and infrastructure. ESA has answered to threats for Earth originating from space in general by initiating the Space-Situational Awareness (SSA) programme in 2008, the goal of whose Near-Earth Object (NEO) segment is to understand and monitor the Solar System's NEO population, to carry out impact assessments and to alert and inform civil authorities in case of emergency.

To achieve these goals ESA plans to improve existing capabilities to establish an integrated NEO observation network which connects several different international telescopes. The data produced will be automatically aggregated and processed by the NEO Coordination Centre (NEOCC) evolving into the Small Bodies Data Centre (SBDC). There, complex algorithms will analyze aggregated NEO data. These algorithms need to be validated despite the fact that there is no integrated network yet. Furthermore, it is planned to expand the currently existing observation network and to improve the detection rate of its components. There is, however, uncertainty about how to better detect NEOs, where to place new observatories and what requirements to be met by observatories.

Because of the before-mentioned demands, project SGNEOP has been carried out resulting in a new NEO population model, a new Optical Sensor Performance Model and the Near-Earth Object Population Observation Program (NEOPOP) software tool (Command-Line Tool and Graphical User Interface, see Figure 1 and Figure 2) containing both. All in all, NEOPOP enables its users to generate, analyze and visualize Near-Earth Object (NEO) populations as well as to simulate, analyze and visualize observations of NEO populations. The first part, based on the new NEO model, is being carried out by the Population Generator component, while the second is the task of the Observation Simulator component.

The new NEO population model has been created by OCA and many other experts. It has been calibrated on and tested against recent observations of Catalina Sky Survey (CSS) and has been created as a successor for the well-known Bottke model which suffers, among others, from invalidity for faint objects and the non-consideration of high-inclination object sources. This new model has been tested more thoroughly than any NEO model before and makes predictions about NEOs with H-values up to 25 (i. e. diameters down to roughly 25-60m) with extrapolation possibility to fainter H and with validity up to H=28.5 (roughly d=5m). It predicts

H-value, orbital (a, e, I) as well as albedo distributions. This state-of-the-art model has been financed partly by this contract (AO/1-7015/11/NL/LvH) and partly by a grant awarded by the Academy of Finland in 2010 (no. 137853). The computation of the biases by R. Jedicke and B. Bolin were supported by both Bottke's NASA Near-Earth Objects Observation grant NNX12AG10G and the University of Hawaii. CSC – IT Center for Science Ltd. provided computational resources. The model has been implemented into NEOPOP by DLR.

The Population Generator component, developed by Technische Universität Braunschweig (TUBS) and German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR) with support of Observatoire de la Côte d'Azur (OCA) and additional experts, is capable of generating fictitious and synthetic populations. A fictitious population consists of a user-selectable amount of objects per object group (Atiras, Apollos etc.) and attributes for which value ranges can be given. Based on this, the tool generates objects in a random fashion. This component also includes the new NEO model described above enabling users to generate synthetic NEO populations based on it. Risk assessments can be carried out using this component, too.

The Observation Simulator component, created by TUBS, can be used for simulating ground- and space-based optical and radar sensor systems that observe NEO populations over a definable period of time. Multiple Monte-Carlo runs can be executed and, as a result, the component tells users which objects crossed which sensor system's field-of-view during which simulation. Also, sensor performance models have been developed as part of this project, the Optical Performance Model being especially advanced. Because of this, the tool additionally outputs which objects crossing sensor system field-of-views could be detected by the defined sensors.

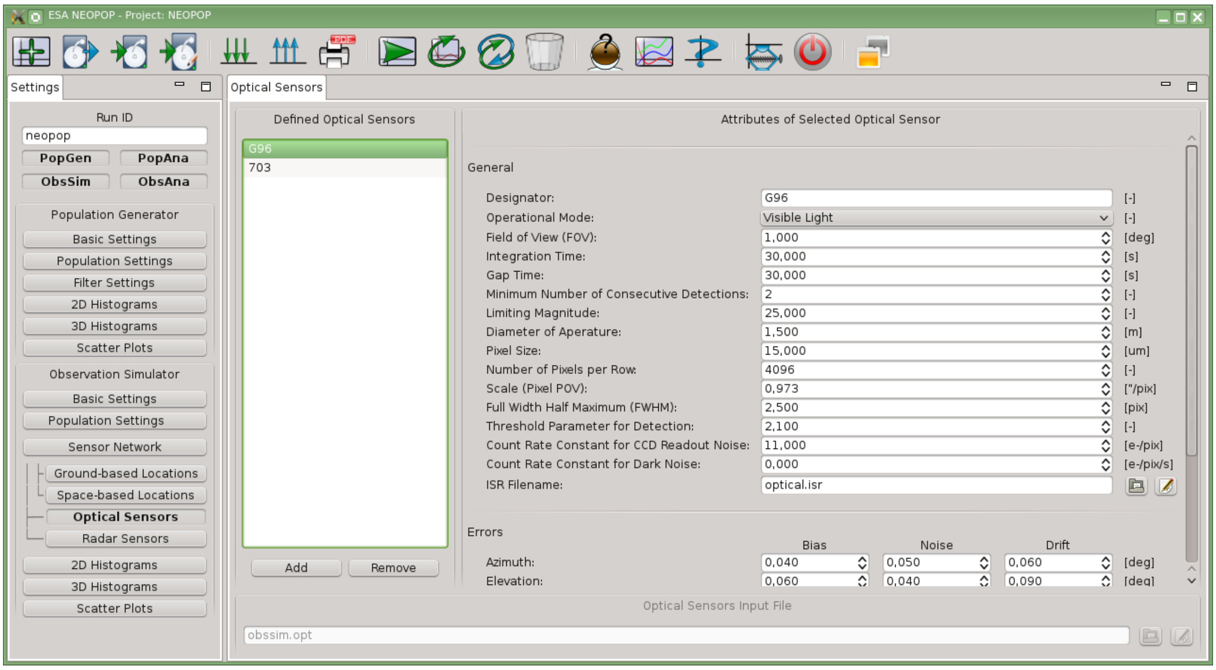

Figure 1: Using NEOPOP (Definition of optical sensors)

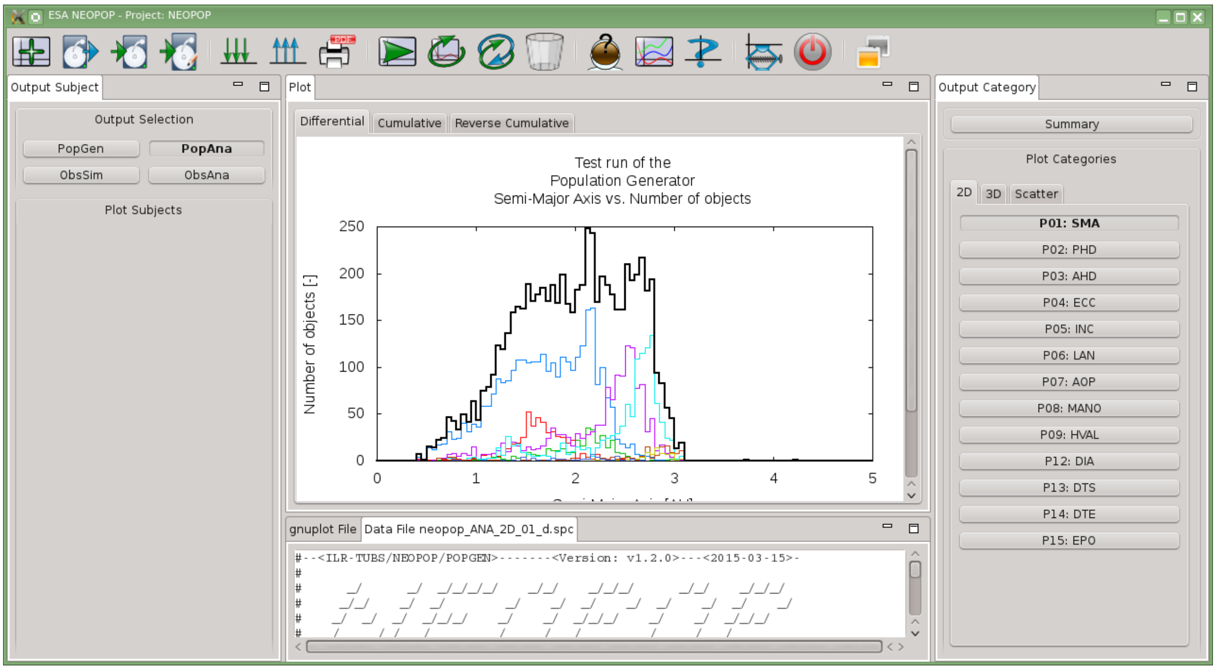

Figure 2: Using NEOPOP (Viewing 2D histogram output)

1.3 Abbreviations

This document contains the following abbreviations:

DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
ILR	Institute of Aerospace Systems (Institut für Luft- und Raumfahrtsysteme)
MPC	Minor Planet Center
NEO	Near Earth Object
NEODyS	NEO Dynamic Site
NEOPOP	NEO Population Observation Program
OCA	Observatoire de la Côte d’Azur
Pan-STARRS	Panoramic Survey Telescope And Rapid Response System
PPF	Physical Properties File
TUBS	Technische Universität Braunschweig, Germany

2 New Population Model

The “new model” by Granvik, Morbidelli, Bottke and collaborators [08] lacks a name at the time of this writing as it has been developed very recently as part of SGNEOP. It has been created as a replacement for the old Bottke model.

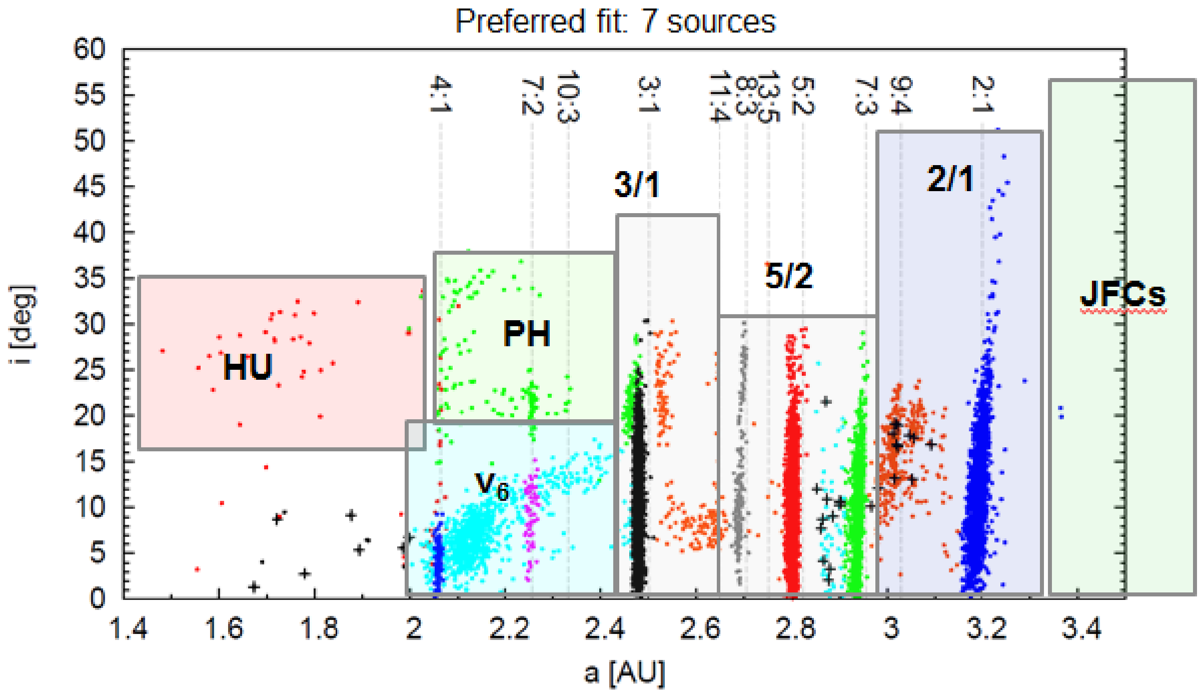

Figure 3: The seven NEO source regions of the new NEO population model.

The scientific approach to build this model is analog to that used in the original model by Bottke. In essence, with numerical simulations the orbital probability distributions $R_k(a,e,i)$ of NEOs coming from different sources within the main asteroid belt (indexed by k) are computed. Whereas the original model considered only 5 sources, the new model accounts for 7 sources (cp. Figure 3), including the high-inclination sources in the Hungaria and Phocea asteroid populations that were lacking in Bottke’s model. A slightly better fit to the data would be achieved using 10 sources. However, among others, the source partition does not include “exotic” ones this way and corresponds to Bottke’s partition.

Moreover, the detection biases B(a,e,I,H) of selected NEO surveys are quantified. Specifically, these are the two Catalina Sky Surveys at Mt. Lemmon (IAU code G96) and Mt. Bigelow (703) which, in the years 2006-2011 performed more than 4000 NEO detections. The NEO model M(a,e,I,H) is then built by combining the different residence time distributions with absolute magnitude distributions $N_k(H)$: $M(a,e,I,H)=\text{sum}_k\ \alpha_k R_k(a,e,i)\ N_k(H)$. The old model assumed that the magnitude distributions $N_k(H)$ are the same for all sources, but the new model has lifted this limitation. The free parameters of the model (the coefficients α_k and those defining the functions $N_k(H)$) are determined by best fit of the biased model, m(a,e,I,H)=M(a,e,I,H) x B(a,e,I,H), to the distribution of NEOs detected by the considered survey, n(a,e,I,H).

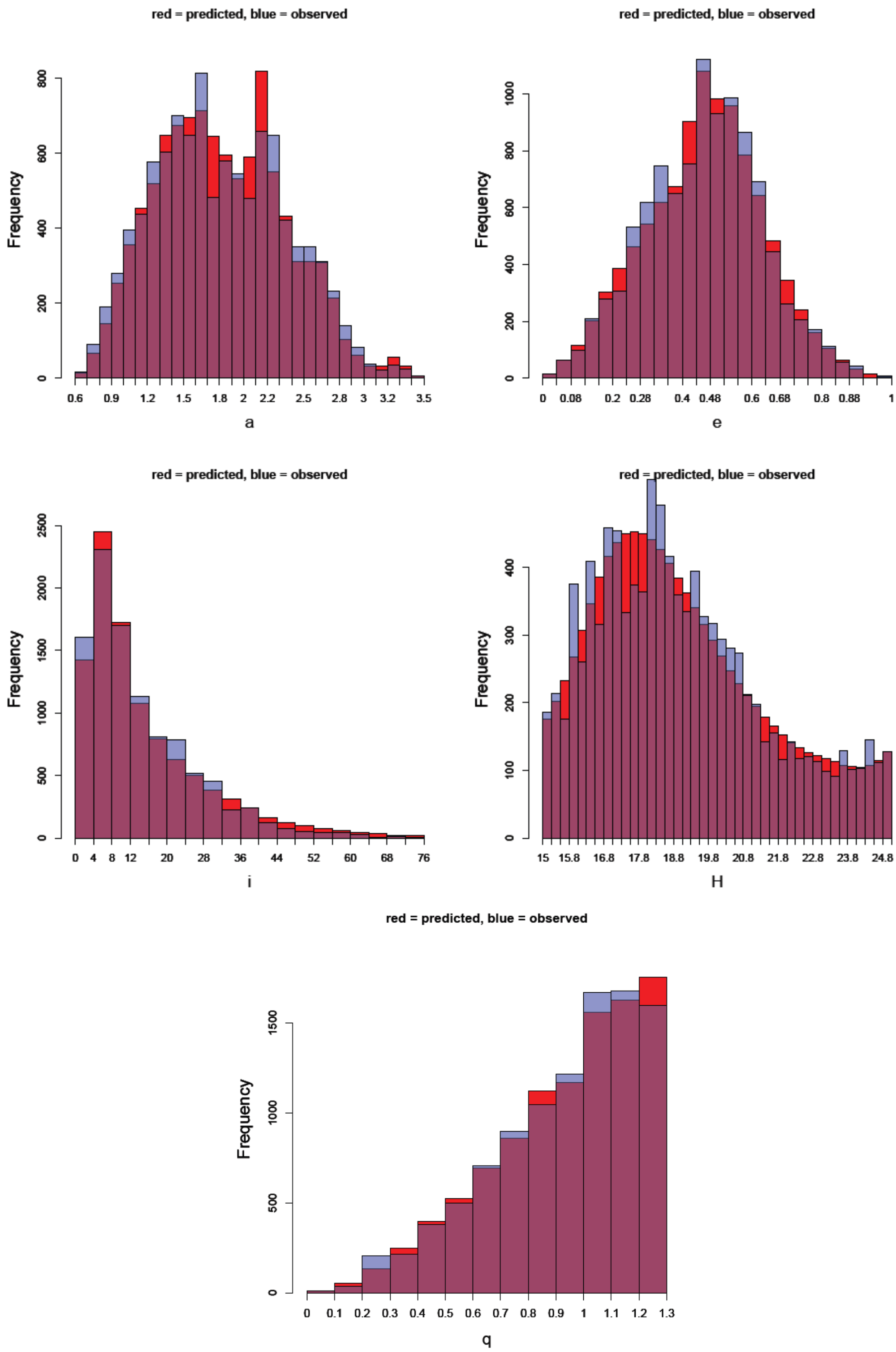

Figure 4: Model calibrated both on G96 and 703 data, compared to both G96 and 703 data.

In a first step the model was built as described using only the data from Catalina's G96 survey and the bias function computed for this survey. As a result the model over-predicted the number of NEOs with small perihelion distances. This effect has been compensated and the study team is currently preparing a paper about this discovery.

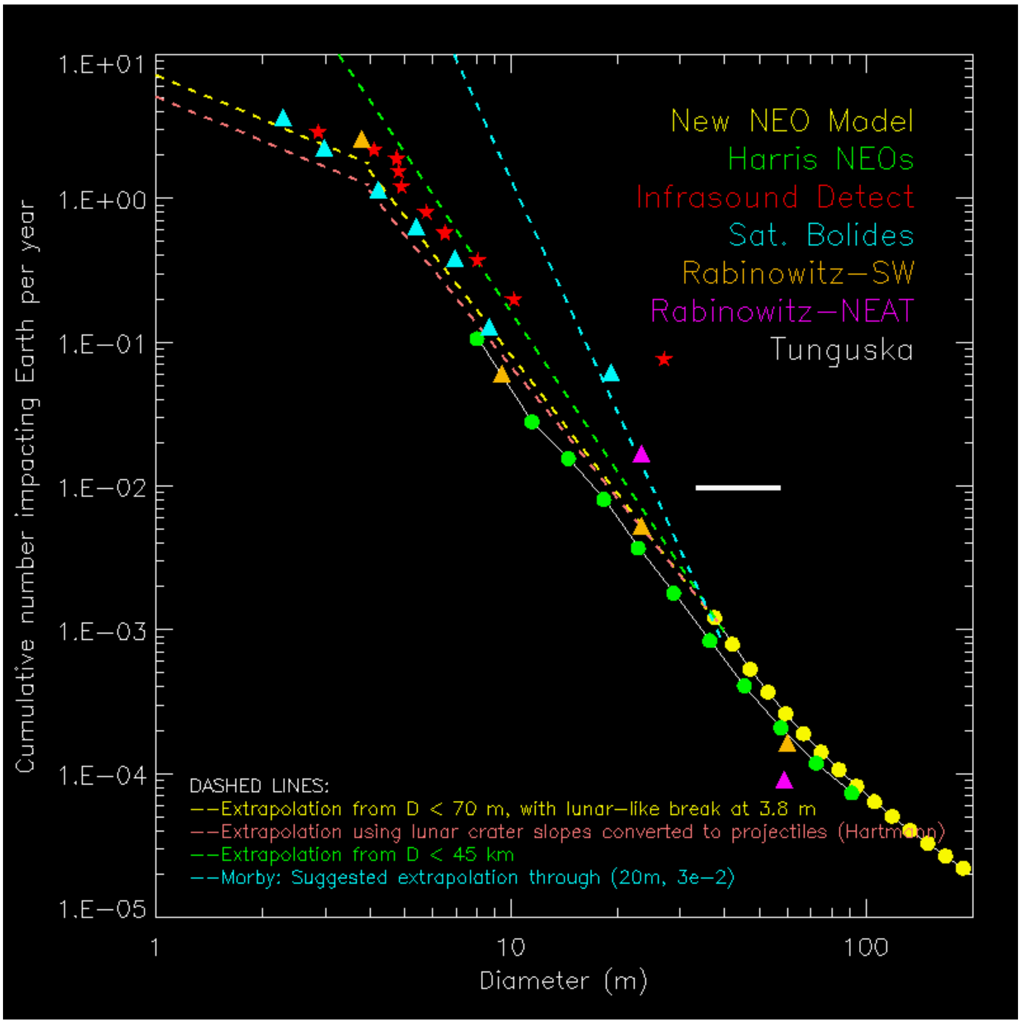

Figure 5: The cumulative number of impacts with the Earth per year, as a function of asteroid size according to different estimates. The yellow dots show the predictions of our model, valid down to D=40m. The other symbols are explained in the plot. The dashed lines show possible extrapolations of the H-distribution of our model to fit the various data (lunar crater distribution, bolide statistics etc.).

The next step was to validate the resulting model against the Catalina 703 survey, by multiplying it with the 703 survey bias and comparing the result with the distribution of NEOs detected by the 703 survey. Notice that the 703 and G96 surveys used very different strategies, so they can be considered truly independent even if they carry the same name “Catalina”. This validation step is therefore a very valid and severe test (no NEO model was tested in this severe way). Once this validation step is done, the biases and the detections of both the G96 and 703 surveys are combined together and a new model is fit in order to benefit from the about double number of data carried by both surveys joined (cp. Figure 4).

The final model (cp. Figure 6 and Figure 7) covers an absolute magnitude range from H=15 up to H=25 and allows extrapolation to fainter H using two different parameter sets – one based on bolide observations by satellites and one based on user-defined power law. This was done to account for the number of impacts per diameter as shown in Figure 5 . The yellow dots indicate the predictions of the new model, the green ones the predictions of Harris NEO model and Rabinowitz NEO model. Triangles and stars show estimates of the occurrence of impacts from satellite observations of impacts in the high atmosphere and infrasound detection of bolide events, respectively. As one can see the data is not very consistent which is why users may define a broken power law distribution by providing a breaking-point in H and two slope parameters.

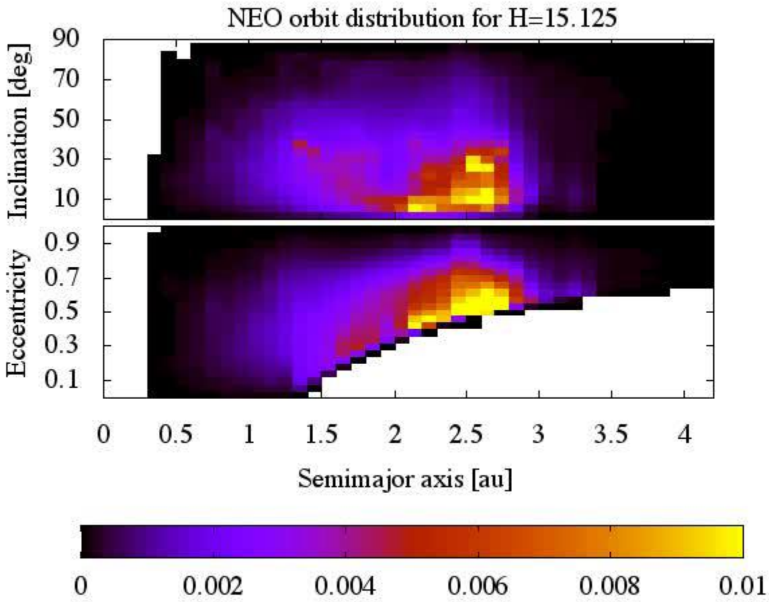

Figure 6: Orbital distribution of the new NEO model.

The model allows predictions of the total number of NEOs in a selectable H-value interval and gives numbers for the four subgroups (Atira, Aten, Apollo and Amor) as well as for the seven NEO source regions (Hungaria, Phocea, Jupiter Family Comets, ν_6, Jupiter 2:1, 5:2 and 3:1 resonances).

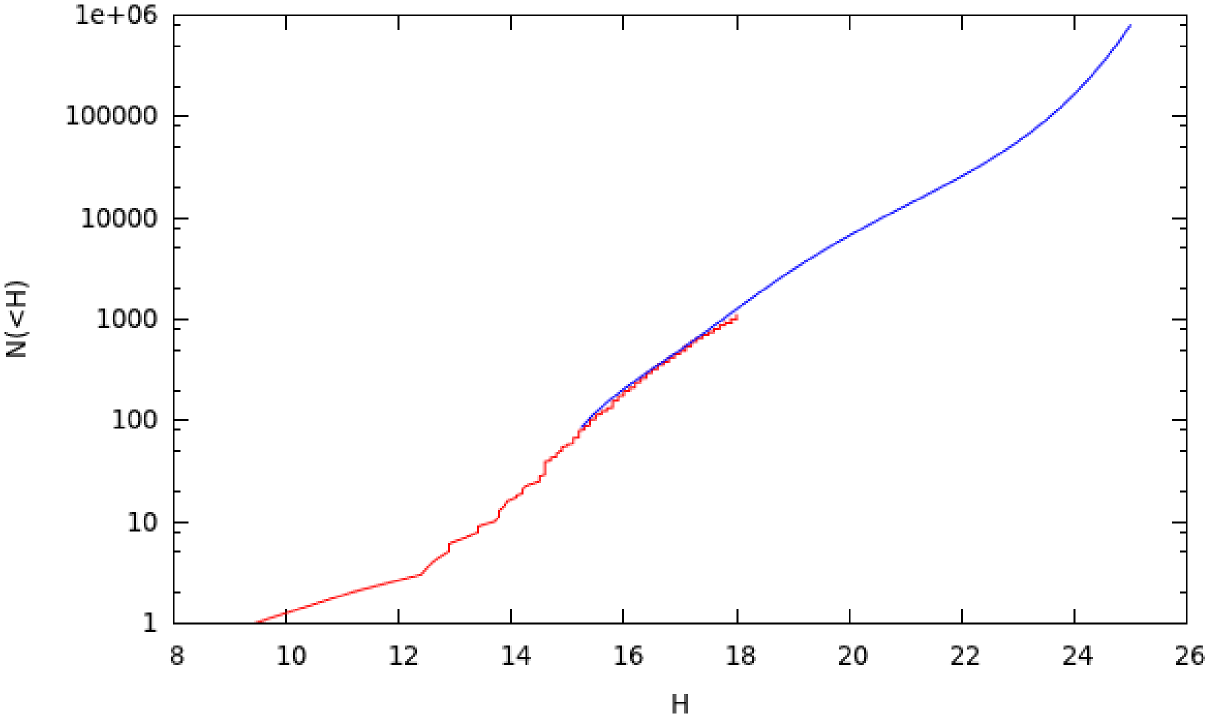

Figure 7: H-value distribution of the new NEO model (blue) and real observation data (red)

The relative contributions of the source regions of the NEO population (cp. Figure 8) can change up to 20% with H. The ν_6 resonance remains the dominant source, if integrated over all values of H, followed by the 3/1 resonance. All other resonances have a minor, although important role. A model constructed using only ν_6 and 3/1 sources would not fit the data well.

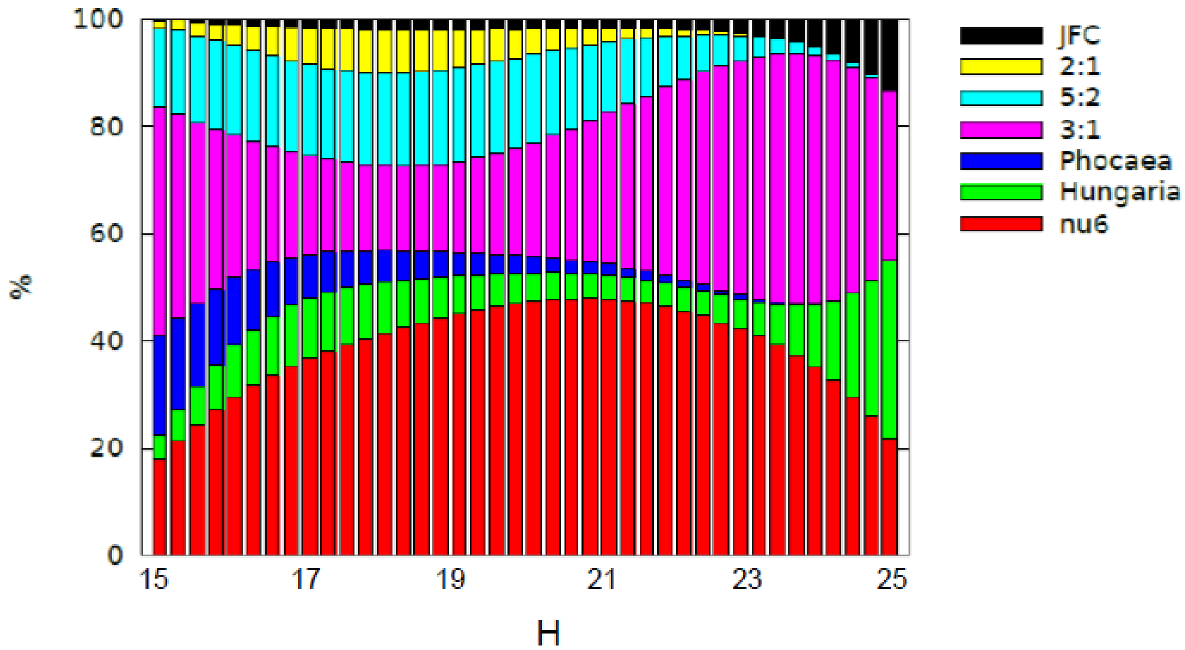

Figure 8: NEO source ratios as a function of H.

Although the current version of the new model achieves good results, final validations are in process and updated versions will be delivered. The model now predicts 1028 NEOs with H<17.75 (d>1km) with the standard deviation being about 100. This shows that the known NEO population up to this value is nearly complete.

This model covers orbital and size distributions of NEOs, but also includes an albedo model, which is based on observations taken from the WISE satellite data (n=394). For this purpose the NEOs are divided into three categories:

- Category 1: Geometric albedo $p_v \leq 0.1$
- Category 2: $0.1 < p_v \leq 0.3$
- Category 3: $p_v > 0.3$

The probability for an object to be in one of these categories depends on its source region. The following table shows the determined values for the probabilities:

Table: Albedo probabilities for the seven sources of NEOs

Source	Probability for being in category…		Error for being in category…	
	1	2	1	2
ν_6	0.120	0.558	0.014	0.003
3/1	0.144	0.782	0.034	0.036
Hungaria	0.021	0.113	0.005	0.004
Phocea	0.501	0.452	0.010	0.020
5/2	0.294	0.557	0.047	0.039
2/1	0.399	0.200	0.015	0.036
JFC	1	0	0	0

Based on these probabilities a reproduction of the WISE data has been carried out. The results were very positive – with one exception: At small perihelion distances the model predicted too many objects in category 1. This can be seen as a symptom of the same issue as described above, namely that the model predicted too many NEOs with low perihelion. This effect has been compensated.

3 Population Generator

One of NEOPOP's two main components is the Population Generator. This component includes the two modules Population Generation and Population Analysis (cp. Figure 9). While the first one can be used to generate a NEO population in different ways, the second one gives the capability to analyze the whole or a subset of a given population and to visualize parameter distributions.

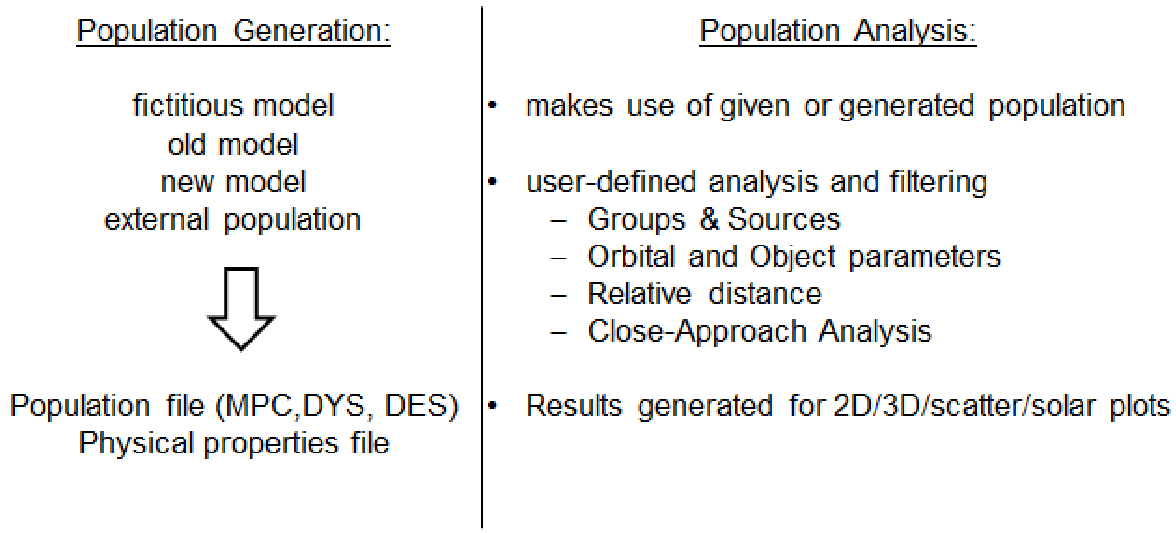

Figure 9: Population Generation and Population Analysis

3.1 Population Generation

The Population Generation module of NEOPOP lets users generate NEO population files of three different types: "DYS" files as used by the NEO Dynamic Site/Asteroids Dynamic Site (NEODys/AstDys) group [05], "MPC" files as used by the International Astronomical Union Minor Planet Center (MPC) in their MPC Orbit (MPCORB) database [04] and finally "DES" files (Data Exchange Standard) as used by the Panoramic Survey Telescope And Rapid Response System (Pan-STARRS) group [06].

This module also creates a Physical Properties File (PPF) for each population file containing further physical properties of each orbit saved in the population file: diameter, minimum orbit intersection distance (if selected), statistical collision probability (if selected), albedo (based on new NEO model), object source (Hungaria, Phocea etc., based on new NEO model), object group (Amors, Atens etc.) and a scaling factor. The scaling factor determines how many actual objects are represented by an orbit. NEOPOP is able to create a PPF for a pre-existing population file.

With this module fictitious – i. e. random – populations may be created. Apollos, Amors, Atens, Atiras and Potentially Hazardous Objects can be selected for generation, their orbit and object parameters may be constrained.

“Synthetic populations” can be generated, too. These are populations with an orbital and absolute magnitude distribution based on scientifically validated NEO models trying to represent the real NEO environment in the best way possible. This enables scientists to analyze the NEO environment and to test hypotheses about it. Two NEO models can be used by NEOPOP users for population generation, both described in the Technical Note [08].

The “old” NEO model implemented in the Population Generation module is the Bottke NEO Model [03]. This model is calibrated on a rather small sample of about 120 NEOs discovered by the Spacewatch Survey prior to 2000. It suffers several shortcomings like its invalidity for NEOs with H>22. Therefore, it is outdated, called the “old model” in context with NEOPOP and should only be used for comparison of the methods, their improvements, and for discussion about technical details.

The “new” NEO model has been developed as part of this project by Mikael Granvik, Alessandro Morbidelli, William Bottke and many other contributors. It is based on and tested against very new observation data and described in chapter 2.

At the bright end, $H < 15$, the population is supposed to be complete. Because of this, NEOPOP, when asked for objects brighter than $H = 15$, doesn’t generate these objects, but instead outputs the known ones based on MPC data.

3.2 Population Analysis

The Population Analysis can be used to analyze and visualize the data contained in population files and PPFs generated by the Population Generation module or files from external sources. Analysis of a given NEO population means propagating the population (using a simple propagator) to a selectable epoch and to filter it by…

- … object group (Atira, Aten, …)
- … object source (ν_6, Jupiter 2:1 resonance, …)
- … given orbital parameter or object property value ranges
- … an object’s distance to Earth or Sun during a defined epoch
- … close-approach analysis regarding Earth for a defined time period and maximum distance

Population objects that do not comply with the filter criteria are skipped from being considered from further processing.

Further processing consists of dumping the filtered population to separate output files (if selected) – which may then be used as input for other modules – and of visualizing the population. Visualization means creating plot definition files for the plotting tool gnuplot [09] which is able to create image files from them. Executing gnuplot has to be done manually, when operating on the command-line, and is done automatically, when using the GUI. It is possible to create 2D (histograms), 3D (third dimension being a “warmth” value), scatter plots and solar system overview plots (polar and side view). Sample plots are shown in Figure 10 . 2D plots come in differential, cumulative and reverse-cumulative variants. Selectable plot axis types include orbital parameters, object properties, the result of the close-approach analysis and more.

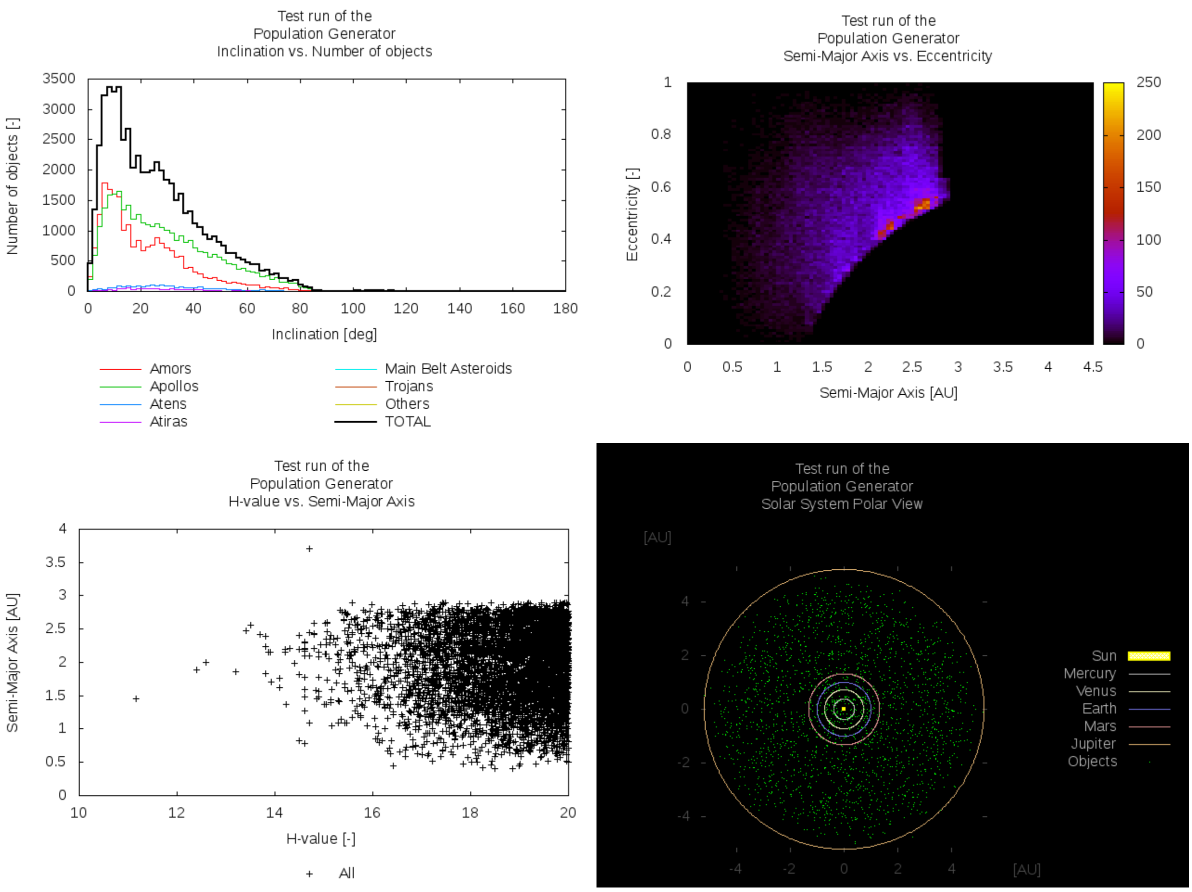

Figure 10: Sample plots of Population Analysis module. From top-left to bottom-right: 2D, 3D, scatter and solar system plot.

4 Observation Simulator

The Observation Simulator is the second component of the NEOPOP software tool. The tasks of this component are covered by its two modules. The module “Observation Simulation” can be used to simulate sensor systems observing Near-Earth Objects. The Observation Analysis module may be used to analyze the results of the simulation and generate the appropriate plots.

4.1 Observation Simulation

The Observation Simulation is the most complex module of the NEOPOP software tool. Its main task is to simulate the behavior of real sensor systems on the ground and in space. This is done especially for optical sensors, which are typically used for the search for asteroids and Near-Earth Objects as done for the Catalina Sky Survey [01]. This module supports the planning of observation strategies, building of sensor networks and testing of algorithms that handle sensor data.

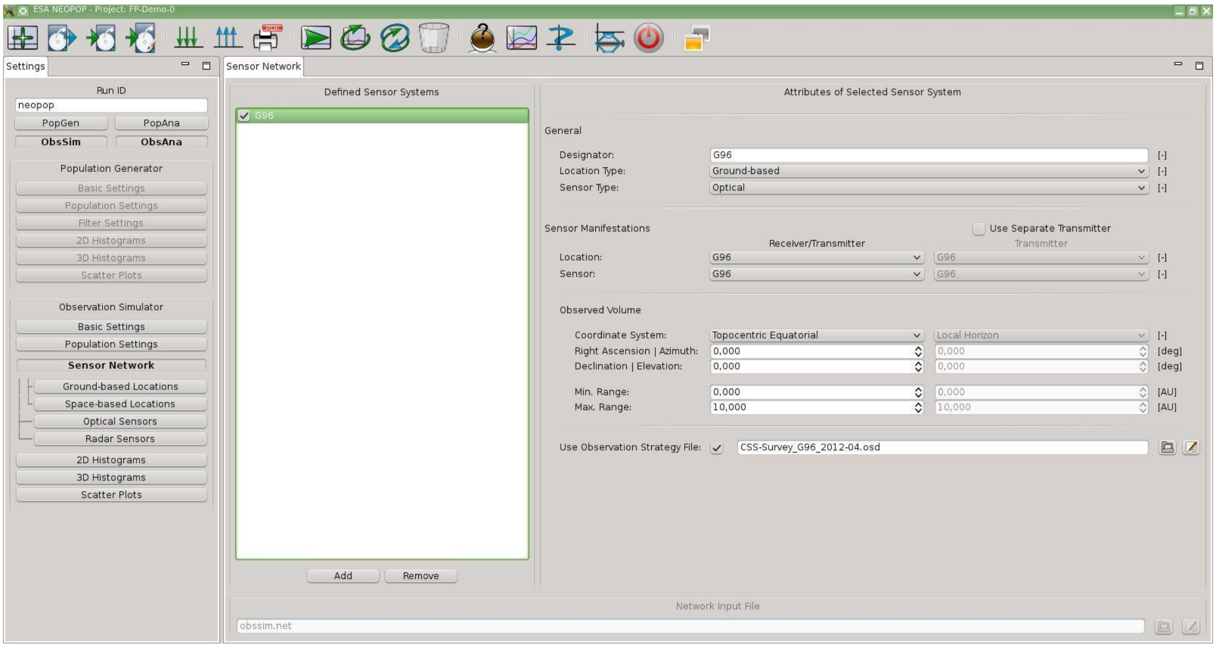

Figure 11: Sensor network definition via NEOPOP GUI.

To use the module, users define a sensor network consisting of ground- and space-based optical and radar sensor systems Figure 11 . Using one or two NEO input populations (in the latter case, the populations are merged) one or more observations can be simulated: in statistical mode the tool carries out a selectable number of Monte-Carlo runs, whereas in deterministic mode no changes to the input orbits are made and only one simulation is executed.

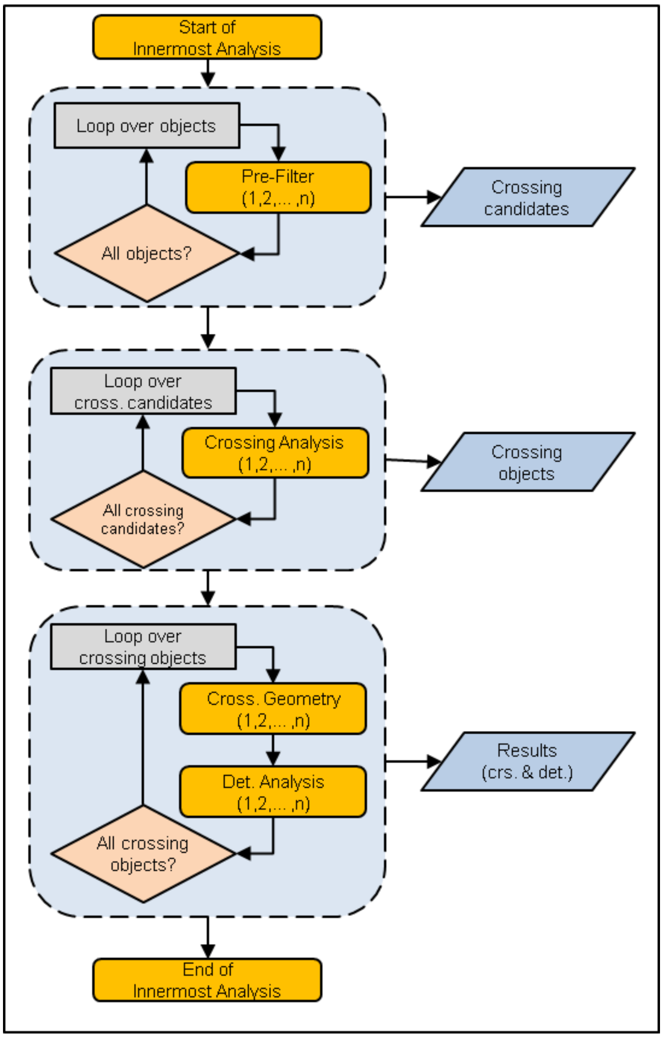

Figure 12: Basic flow chart of the module Observation Simulation.

The simulation first runs the Pre-Filter which skips all objects that, by any means, can't cross the simulated sensor system's field of view (cp. Figure 12). The objects that are not skipped are the "crossing candidates" that serve as input for Crossing Analysis. This step checks if an analyzed object crossed a sensor system's field of view (FOV), i. e. that the object can theoretically be detected by a sensor system. For each of the resulting "crossing objects" or "crossings" a so-called crossing geometry is computed consisting of a set of the following form: (epoch, state vector, line-of-sight direction). It depicts the positions and velocities of a crossing object during its passing of the FOV for a specific point in time and also states in which direction the sensor was looking at that time. The crossing geometries are then given as input to the sensor performance model corresponding to the sensor's type (radar or optical).

The module outputs a results file for each sensor system and simulation listing objects that have crossed the sensor system's field-of-view. The list includes object properties as found in the population file and PPF as well as lots of additional observation attributes like the type of crossing (e. g. has it been detected by the sensor?), field-of-view dwell time, time of closest approach etc.

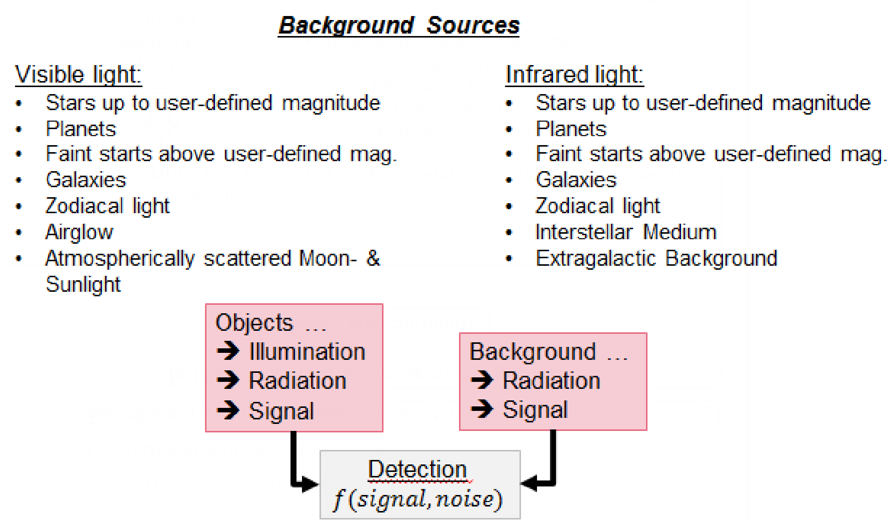

Figure 13: Background signal sources considered in the Optical (Sensor) Performance Model (OPM).

As mentioned above, an optical and radar sensor model are part of the software; they enable NEOPOP to output if a sensor system actually was able to detect the objects that crossed its field-of-view. The Optical (Sensor) Performance Model (OPM) is very advanced. It calculates the object signal and compares it to a background signal that takes into account many different background sources like zodiacal light and galaxies (cp. Figure 13).

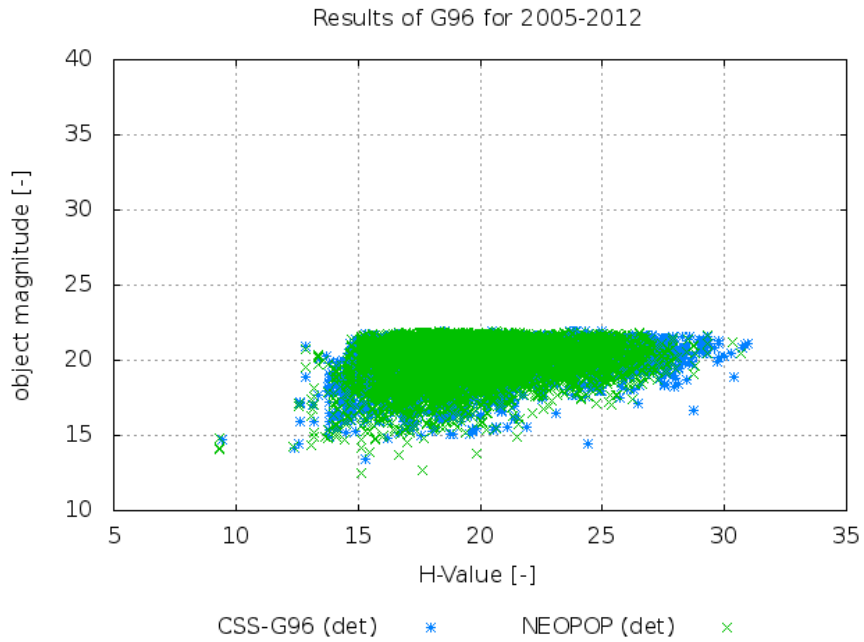

Figure 14: Comparison between the real NEO detections of Catalina Sky Survey (CSS), Mt. Lemmon station (G96), and the detections output by NEOPOP for said survey.

Figure 14 shows the validation results of the OPM based on Catalina Sky Survey data. Apart from the high-H region, a good agreement can be seen between detections of the real and the simulated survey.

Further functionalities of the Observation Simulation module are:

- Configuring a sensor system's parameters, like its orientation, to change during observation using so-called Observation Strategy Files
- Creation of data for "sky plots" which show the whole sky from a sensor system's point-of-view telling users which part of the sky would yield how many crossings and detections at a specific epoch when pointing the sensor in the respective direction
- Creation of artificial sensor system measurements

4.2 Observation Analysis

The Observation Analysis module has the same task as the visualization part of the Population Analysis module: It is responsible for the generation of plot definition files which have to be executed by the plotting tool gnuplot to generate plots. There is no scientific part included in this module. In contrast to the Program for Radar and Optical Observation Forecasting (PROOF) software [02], the analysis is a separate module for being able to analyze the results independent from the simulation, which can be very time consuming.

The same plot types as for Population Analysis are available (2D, 3D, scatter and solar system overviews). Additionally, sky plots may be created (see section 4.1), which are implemented as a special type of 3D plot. The selectable plot axis types differ to some extent (observation-specific attributes can be selected, too, for example).

5 Conclusion

Overall, the project "Synthetic Generation of a Near-Earth Object" has been a success: It resulted in a new sophisticated NEO model. As part of the newly created software tool NEOPOP, which also includes multiple filtering and plotting functionalities, users can get new insight into the NEO environment. Using the newly created sophisticated Optical Sensor Performance Model, observation simulations of the NEO environment are possible benefitting the installation of the upcoming ESA NEO observation network by the assessment of observation strategies, sensor and sensor location properties, providing artificial measurements and more.

5.1 Deliverables

The deliverables of this project include:

- Documents (Format: PDF and DOC):
    - Design, Development and Validation Plan, v5.0
    - Requirements Baseline, v3.2
    - Technical Specification, v3.3
    - Design Definition File, v3.6
    - Design Justification File, v2.7
    - Technical Note "Modeling the NEO population", v3.7
    - Software User Manual, v2.0
    - Final Report, v2.0
    - Software Release Note, v2.0
    - Executive Summary, v2.0
    - Web Article, v1.2
    - Publication List, v1.3

- Test environment:
    - Test Kit
    - Test Result Projects

- Software Release:
    - NEOPOP v2.0 Software Installation Package consisting of:
        - NEOPOP Installer
        - NEOPOP Graphical User Interface (GUI)
        - NEOPOP Command-Line Tool (CLT)
        - NEO model v5.0 (delivered 07.05.2015)

- Problems and Remarks:
    - List of Review Item Descriptions (RIDs)
    - List of Software Problem Reports (SPRs)

- Presentation:
    - Final Presentation Slides, v1.1

In addition, the software NEOPOP has been delivered as source code containing the following parts:

- Fortran Sources:
    - Source code of a library, containing basic routines (e.g. logfile handling, etc.)
    - Source code of the Population Generation
    - Source code of the Population Analysis
    - Source code of the Observation Simulation
    - Source code of the Observation Analysis
    - Source code of the Radar Performance Model
    - Source code of the Optical Performance Model
    - Source code of the NEOPOP front-end

- Java Sources:
    - Main source code of NEOPOP Graphical User Interface consisting of several Eclipse projects
    - delta pack used for cross-platform build exports
    - log4j used for logging, packed as Eclipse project

In addition, the SPICE library is required to compile and execute NEOPOP. This package is not a deliverable but can be accessed via http://naif.jpl.nasa.gov/naif/

5.2 Further Improvements

NEOPOP already offers an extensive amount of functionality. Nevertheless, software is never completely "done" which is why some ideas for improvements always exist.

The radar model used, for example, is a simple one based on the basic radar equation. An idea for a more advanced model would be to take into account the coherent integration of radar pulses. This is currently an important field of research and a radar model based on this idea would enable NEOPOP users to simulate radar sensors specifically adjusted for NEO detection. And, since NEOPOP is built modular, the new radar model could relatively easily be integrated into the software. A follow-up project to SGNEOP addressing this matter is already in preparation.

Parallelization would be another point. NEOPOP in general and the Observation Simulation's Detection Analysis are already prepared to be parallelized. However, NEOPOP makes use of the FORTRAN toolkit named SPICE which has not been implemented with parallelization in mind. One possibility to solve this issue would be to replace SPICE routines with something similar which would be easier to adjust for parallel computing. However, using SPICE has proven to be valuable as, for example, planetary ephemeris data can easily be used. The second possibility would be to adjust SPICE. It has become clear during the project though that an adjustment of SPICE would not fit into the project's boundaries.

Finally, observation simulations with long observation durations also could be a point of interest for further work. The SGNEOP Requirements Baseline states that the software should allow observations of up to 10 years. Nevertheless, this limit has been raised to 68 years, but these long simulations have not been tested thoroughly. And it should be investigated if even longer observation durations are wanted by users.

6 References

[01] The Catalina Sky Survey, (Source http://www.lpl.arizona.edu/css/index.html, March 8th, 2014)

[02] J. Gelhaus, “Final Report – Program for Radar and Optical Observation Forecasting”, Institute of Aerospace Systems, TU Braunschweig, Germany, May 2011, ESA Contract 21705/08/D/HK

[03] W.F. Bottke, A. Morbidelli, R. Jedicke, J.-M. Petit, H.F. Levison, P. Michel, T.S. Metcalfe, “Debiased Orbital and Absolute Magnitude Distribution of the Near-Earth Objects”, Icarus 156 (399-433), 2002

[04] Homepage of the Minor Planet Center orbital database, www.minorplanetcenter.net/iau/MPCORB.html

[05] Homepage of the NEODyS database, http://newton.dm.unipi.it/neodys/

[06] Pan-STARRS Data Exchange Standard (DES 2.02) PSDC-MOPS-DES-2.02, http://adams.dm.unipi.it/orbfit/PS_DES_v2.02.pdf

[07] J. Gelhaus, G. Hahn and S. Müller, “*The Near Earth Object Population Observation Program*”, Final Report, ESA/ESTEC Contract No: 4000106274, September 2014

[08] G. Hahn, M. Granvik, A. Morbidelli, P. Michel, R. Jedicke, B. Bolin, B. Bottke, D. Nesvorny, D. Vokrouhlicky and E. Beshore: “Modeling the NEO Population”, Technical Note, ESA/ESTEC Contract No: 4000106274, December 2014

[09] T. Williams, C. Kelley, et.al., “*GNUPLOT - An Interactive Plotting Program*” , Version 4.4.4, November 12th, 2011 (Source: http://www.gnuplot.info/docs_4.4/gnuplot.pdf, 09.05.2013)

[10] Jedicke, R.; Bolin, B.; Granvik, M.; Beshore, E.: “An improved technique for quantifying observational selection effects in asteroid surveys”. Icarus. In revision.

[11] Granvik, M.; Morbidelli, A.; Beshore, E.; Bottke, W.; Jedicke, R.; Michel, P.; Nesvorny, D; Vokrouhlicky, D.: “Disruption of asteroids at small perihelion distances”. In preparation.

[12] Granvik, M.; Morbidelli, A.; Bottke, W.; Jedicke, R.; Michel, P.; Nesvorny, D.; Vokrouhlicky, D.: “Source populations for near-Earth objects”. In preparation.

[13] Granvik, M. et al. (author list tbd): “Debiased orbit and absolute-magnitude distributions for near-Earth objects”. In preparation.

[14] Morbidelli, A.; Delbo, M. et al. (author list tbd): “NEO albedo model”. In preparation.

[15] Mueller, S.; Gelhaus, J.; Hahn, G.; Franco, R.: “A NEO Population Generation and Observation Simulation Software Tool”. Poster presentation B0.4-0062-14, Committee on Space Research (COSPAR) Scientific Assembly in Moscow (COSMOS) 2-10 August 2014, Moscow, Russia.

[16] Mueller, S.; Gelhaus, J.; Hahn, G.; Franco, R.: "A NEO Population Generation and Observation Simulation Software Tool". Advances in Space Research, in preparation.

[17] Greenstreet, S.; Gladman, B: "High-inclination Atens are Indeed Rare". The Astrophysical Journal 767, LL18. 2013.

[18] Greenstreet, S.; Gladman, B.; Ngo, H.; Granvik, M.; Larson, S: "Production of Near-Earth Asteroids on Retrograde Orbits". The Astrophysical Journal 749, LL39, 2012.

[19] Greenstreet, S.; Ngo, H.; Gladman, B: "The orbital distribution of Near-Earth Objects inside Earth's orbit". Icarus 217, 355-366. 2012.

[20] Harris, A. W. "Estimating the NEO Population and Impact Risk: Past, Present and Future". Protecting the Earth against Collisions with Asteroids and Comet Nuclei 312. 2010.

[21] Mainzer, A. and 10 colleagues: "The Population of Tiny Near-Earth Objects Observed by NEOWISE". The Astrophysical Journal 784, 110. 2014.

[22] Mainzer, A. and 12 colleagues: "Characterizing Subpopulations within the near-Earth Objects with NEOWISE: Preliminary Results". The Astrophysical Journal 752, 110. 2012.

[23] Granvik, M., Morbidelli, A., Jedicke, R., et al: "Unbiased dynamical and physical characteristics of the near-Earth-object population". Asteroids, Comets, Meteors 2014 180.

[24] Granvik, M: "New population-level insights about near-Earth objects". Proceedings of IAU Symposium 2015, S318.1.01.

7 Annex

1. Abstract of “An improved technique for quantifying observational selection effects in asteroid surveys” [10]
2. Full text of “A NEO Population Generation and Observation Simulation Software Tool “ [15]
3. Abstract of “Unbiased dynamical and physical characteristics of the near-Earth-object population” [23]
4. Abstract of “New population-level insights about near-Earth objects” [24]