

Stardust-Reloaded: The H2020 Space Debris and Asteroid research network

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Project: Asteroid families in the Proper Elements Space

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Purpose:

The ESRs should:

- be able to understand the main steps of the procedure to compute the proper orbital elements of asteroids
- be able to understand the main difference between the osculating and proper orbital elements
- learn basics about the codes used to compute the proper elements
- be able to identify the main problems and limitations in the computation and exploitation of the proper elements
- to familiarize themselves with the web-pages providing osculating and proper orbital elements of asteroids, and data on asteroid families
- to apply machine learning tool(s) to classify asteroids into families, using the proper elements data

Brief introduction:

Asteroid proper orbital elements are quasi-constants of motion, that remain practically unchanged over long time spans. These elements serve as parameters for classification of asteroids into families, and as a tool to study their long-term dynamics. The most accurate proper elements are obtained by applying the so-called synthetic theory, that consists of purely numerical procedures. It includes the numerical integration of the asteroid orbits carried out in the framework of a suitable dynamical model, on-line digital filtering of the short-periodic perturbations to produce mean elements, removal of the forced oscillations, and the Fourier analysis of secular time series to remove long-periodic perturbations and compute the proper orbital elements.

The first step, that is numerical orbit propagation, is performed starting from the instantaneous osculating orbital elements. The osculating elements are obtained from the observations, and are available at [AstDyS](#) and [NEODyS](#) web pages, maintained by University of Pisa¹. Once the numerical integrations of orbits are completed, these data are then used to compute the proper elements. A public domain *OrbFit* package can be used for both, orbit propagation and proper elements computation. The obtained set of asteroid proper elements should then be analyzed in order to identify possibly statistically significant clusterings. In this last step, machine learning techniques should be involved, and the aim should be to test at least two different clustering algorithms.

¹ The osculating orbital elements of asteroids are also provided by other web-services, such is the [Jet Propulsion Laboratory \(JPL\)](#), and the [Minor Planet Center \(MPC\)](#).

Technical description:

Here we describe the main steps that should be taken in order to complete this exercise. You will use a numerical integration program called [ORBIT9](#) to perform your long-term integrations. ORBIT9 is one of the workhorses of the professional astronomical community to determine the behavior of small bodies in the Solar System. It has been used in large number of publications in the scientific literature. ORBIT9 is designed to integrate a set of mutually gravitationally interacting bodies (usually planets) together with a group of test particles (usually asteroids) that feel the gravitational influence of the massive bodies but do not affect each other or the massive bodies. ORBIT9² numerical integrator executable code and necessary input files are available at <https://github.com/stardust-r/LTW-I/tree/master/Asteroid%20Families/Orbit9> To make the code executable on an UNIX machine you may use e.g. `chmod +x orbit9` from the command line. In addition, you will need a small code named PROPSYNTH to compute proper elements from the integrations that you will perform, and should also use PYTHON or MATLAB to visualize some data.

The last task will be to implement unsupervised machine learning based clustering algorithms (in PYTHON or MATLAB) to identify asteroid clusters³. This identification should be performed in 3D proper elements space (proper semi-major axis, proper eccentricity and sine of proper inclination). The standard metrics to measure distances in this space should be used, as defined in [2].

The following steps should be performed:

Step 1: Download a catalog of osculating orbital elements from [AstDys](#) web page maintained by University of Pisa. A link to the catalog of numbered main-belt asteroids is this one: <https://newton.spacedys.com/~astdys2/catalogs/allnum.cat>

Step 2: Download ORBIT9 numerical integrator executable code and necessary input files from <https://github.com/stardust-r/LTW-I/tree/master/Asteroid%20Families/Orbit9> To make the code executable on an UNIX machine you may use e.g. `chmod +x orbit9` from the command line

Step 3: Pick up randomly 10 asteroids with semi-major axis between 2.3 and 3.2 au, and perihelion distance $q = a(1-e)$ larger than 1.7 au, from [allnum.cat](#). Then propagate the orbits of these objects for 2 Myr (see appendix on basic instructions on how to use the software). To this purpose you should use 7-planets dynamical model (from Venus to Neptune). *This may take about 15-20 minutes!*

Step 4: Redo the integrations for 10 selected asteroids using the 4-planets dynamical model (from Jupiter to Neptune). The other settings should be the same. *But, be careful about the barycentric corrections! This should take some time, but less than the integrations in step 3.*

Step 5: Download PROPSYNTH code from [this link](#).

Step 6: Compute proper orbital elements of 10 selected asteroids using PROPSYNTH code and the numerical integrations produced by ORBIT9 (steps 3 and 4). *Compare and discuss the difference in proper elements obtained within two dynamical models. For which asteroids differences are larger and why?*

Step 7: Download a catalog of proper orbital elements from [AFP](#) web page maintained by University of Belgrade, available at <http://asteroids.matf.bg.ac.rs/fam/proper/afp.pro> For information on the [afp.pro](#) file format please visit <http://asteroids.matf.bg.ac.rs/fam/properelements.php>

Step 8: For 10 selected asteroids, compare their proper elements from the catalog, with the ones you computed. *Briefly comment on how much (if at all) the results are different, and discuss possible reasons for these differences.*

Step 9: Use PYTHON or MATLAB to visualize distribution of asteroids in the proper semi-major axis vs sine of proper inclination and/or proper semi-major axis vs proper eccentricity plane. *Hint: if there*

² Orbit9 integrator is a part of OrbFit software package. For more information please visit <http://adams.dm.unipi.it/~orbmain/orbfit/>

³ https://hdbscan.readthedocs.io/en/latest/how_hdbscan_works.html

are too many points for clear presentation, use only a part of the catalog. *Is the distribution uniform? If not, in your opinion, what would be possible explanations?*

Step 10: Use [HDBSCAN](#) clustering algorithm to the catalog of asteroid proper elements to classify asteroids into groups. For this purpose extract asteroids from the [afp.pro](#) catalog with proper semi-major axis between 2.5 and 2.82 au, and sine of proper inclination above 0.3. *Test and comment on how the classification depends on the parameters of the algorithm.*

Important note: Each time you run ORBIT9, *don't forget to do this in a new working directory, otherwise you will overwrite the output files from the previous integrations!*

Literature:

Main references:

1. Knežević Z., Milani A., 2003, **Proper element catalogs and asteroid families**. *Astronomy and Astrophysics* 403, 1165
2. Zappala, V., Cellino, A., Farinella, P., Knežević, Z. 1990. **Asteroid Families. I. Identification by Hierarchical Clustering and Reliability Assessment**. *The Astronomical Journal* 100, 2030

Additional references:

3. Carruba, V., Aljbaae, S., Lucchini, A. 2019. **Machine-learning identification of asteroid groups**. *Monthly Notices of the Royal Astronomical Society* 488, 1377
4. Milani, A., Cellino, A., Knežević, Z., Novaković, B., Spoto, F., Paolicchi, P. 2014. **Asteroid families classification: Exploiting very large datasets**. *Icarus* 239, 46
5. Nesvorný, D., Brož, M., Carruba, V. 2015. **Identification and Dynamical Properties of Asteroid Families**. *Asteroids IV* 297, University of Arizona Press
6. Knežević, Z. 2017. **Computation of Asteroid Proper Elements: Recent Advances**. *Serbian Astronomical Journal* 194, 1



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APPENDIX - A

Basic user guide for ORBIT9 code

Setup: ORBIT9 takes four input files: **orb9.opt**, **barcor.inc**, **planets.inc** and **input.cat**. Input file **orb9.opt** tells the code how to perform the calculation, **planets.inc** supplies the initial conditions of the planets, **barcor.inc** provides data for barycentric corrections (if applied), and **input.cat** gives the initial positions of the small bodies. You will need these files before you run the code. In addition, you should copy these three files in the working directory of ORBIT9: **filter.100**, **random.dat**, and **rk.coe**.

- **orb9.opt** file is used to set the integrations performed by ORBIT9
- **barcor.inc** - provides barycentric correction data for a given epoch
- **planets.inc** - provides initial conditions for planets, for a given epoch
- **input.cat** - provides initial conditions for planets, for a given epoch

To run intergrations with ORBIT9, only **orb9.opt** file should be properly set. An example of the **orb9.opt** file is shown below, and options that need to be set are highlighted in bold.

;input control and options file for orbit8

; 1. input file names

inplan='planets.inc'; input file name for initial conditions of the planets

ibar= 1; barycentric correction 1=yes 0=no

inbar='barcor.inc'; file containing the barycentric correction

inast='input.cat'; input file name for initial conditions of the asteroids

; 2. job description: ast. are ordered in two list, with and without LCE

nvz= 5 ; no. Lyapounov exponents

4

10

24

490

11805

; 3. options: output \$ = option not yet implemented

dt= -100.d0 ; time between two outputs

nout= 20000; output number at job termination

idump= 500; number of outputs between dump/renormalisation

nsamp= 100; sampling ratio of the filter; choose 5, 20,50 or 100

iprqua= 1; how much output: 1 elem. filtr; 2 also sampl.;

sysz= 'HEL' ; output system: BAR, HEL, JAC, HEC

refz= 'INVL1B' ; output reference system: INVL1B, ECLM50, EQUM00, etc

; 4. options: variational equation

v1= 1.00d+06; variation vector norm forcing renormalisation

semim= 3.0; approx. semimajor axis for norm of var.vect.

; 5. options: propagator

h= 0.2; stepsize for multistep (maximum stepsize if automatic)

iauto= 1; automatic stepsize control 1=on 0=off

error= 1.d-13; target integration error, radians/revolution^2

iord= 12; order of multistep predictor

epms= 0.0d-12; convergence control for corrector \$

iork= 12; order of starter

eprk= 1.00d-10; convergence control for implicit Runge-Kutta

lit1= 10; iterations for first step

lit2= 4; iterations for following steps

imet= 1; main integration method: 1 multistep 2 symplectic

```

iusci=10; output of numerical convergence controls 0 no
icha=1; what to do if non convergent 0 interactive 1 batch, change step $
ll=12; control for Everhart (>0 automatic stepsize control)
; 6. control of close approach output
dmint=0.01; close appr. distance for terrestrial planets
dminj=0.1; close approach distance for giant planets
npoint=10; minimum number of data points for a deep close appr.
; 7. optional perturbations
irelj2=0; relativistic and J2 perturbations 0=no 1=yes
iyark=0; Yarkovsky effect as secular drift in a 0=no 3=yes 1,2=not in use
; END OF INPUT

```

IMPORTANT: Explanations for the lines that need to be edited:

- **inplan='planets.inc';** this is the name of the input file containing initial conditions of the planets. Usually a file called **pvenexx.inc** contains the data for seven planets, and a file named **planxx.inc** provides the initial conditions for the four planets dynamical model
- **inbar='barcor.inc';** this is the name of the file containing the barycentric correction. Usually a file called **barmerxx.inc** contains the data for seven planets, and a file named **barsunxx.inc** provides the barycentric correction for four planets
- **inast='input.cat';** the name of the input file with initial conditions for the asteroids. You may need to change it to **allnum.cat**, in order to use catalog downloaded from AstDys
- **nvz= 5 ;** number of asteroids for which Lyapunov exponent will be computed. It is usually the same as the number of asteroids to be integrated
- **Below the "nvz", please provide a list of all asteroids whose orbits you would like to propagate. Note that one asteroid per line should be provided!**

Explanations for some important settings that you do not need to modify:

- **dt= -100.d0 ;** time between two outputs
- **nout= 20000;** output number at job termination
- "dt" is a time between two outputs, while the "nout" is the number of outputs. Therefore, a total integration time may be obtained by multiplying "dt" and "nout". Note that a negative value of "dt" indicates backward orbit propagation
- **iprqua= 1;** how much output: 1 elem. filtr; 2 also sampl. ORBIT9 provides two types of outputs: osculating elements and mean (filtered) elements. The mean elements are obtained by "on-line" removing short-periodic oscillations from the osculating elements. Option "iprqua" sets whether to print both type of elements (option 2), or only mean elements (option 1). *Note that for computation of the proper elements, the mean elements are used!*
- **h= 0.2;** stepsize for multistep (maximum stepsize, in years, if automatic) The step size is usually determined automatically. In case you want to enter it manually, you should ensure it is at least about 1/25 of the smallest orbital period in the problem, preferably about 1/50.
- **iauto= 1;** automatic stepsize control 1=on 0=off. Here you chose between the automatic and manual integrator step control. If you turn off automatic control, please see the previous point.

Outputs: ORBIT9 provides the following outputfiles files: **orb9.clo**, **orb9.dma**, **orb9.dmp**, **orb9.num**, **orb9.out**, **vast.fil**, **vpla.fil** and (optionally) **vast.dat** and **vpla.dat**.

- **orb9.clo** - contains data on close approaches between the small bodies and the planets
- **orb9.dma** and **orb9.dmp** - dump files used to extend integrations
- **orb9.num** - provides some data on the process of numerical integration
- **orb9.out** - data on the integration initial conditions
- **vast.fil**, **vpla.fil** - time series of mean orbital elements for asteroids and planets, respectively
- **vast.dat**, **vpla.dat** - time series of osculating orbital elements for asteroids and planets, respectively

Note: for the computation of proper elements, only the **vast.fil** file is needed!

APPENDIX - B

Basic user guide for PROPSYNTH code

Setup for PROPSYNTH code is very simple. It uses the mean orbital elements produced by ORBIT9 code, in order to compute the proper elements. The mean elements for asteroids are typically stored in the file named **vast.fil**. As PROPSYNTH code assumes that the name of the input file ends with "ast.fil", when starting the PROPSYNTH code, it will ask you to provide "initial part of file names", and you should type "v". Also, as your **vast.fil** file contains 20,000 records, for the second option "running box flag 1 = 10000 recs; 2 = 20000 recs outer belt; 3 = 20000 recs inner belt, TNO", you should select option "3". See figure below.

```
bojan@bojan-UX305UA:~/Documents/Projects/Stardust_Reloaded/LTW-I_Madrid2020/ProperElementsProject/software_test$ ./propsynth
initial part of file names?
v
running box flag 1 = 10000 recs; 2 = 20000 recs outer belt; 3 = 20000 recs inn
er belt, TNO
3
asteroids from : 910001      to : 910005
end of file, number of records      19989
nbeg,naf      1      5
data from t= -600.0000 to t= -1999400.0000 no datapoints=19989
together      10000      step      997
1      10000
998      10997
1995      11994
2992      12991
3989      13988
4986      14985
5983      15982
6980      16979
7977      17976
8974      18973
9971      19970
nbeg,naf      356      0
```

Outputs: PROPSYNTH provides the following output files: **vprs.ang**, **vprs.err**, **vprs.out**, **vprs.pro**, **vprs.sig** and **vprs.del**.

- **vprs.ang** - some additional data on angular orbital elements
- **vprs.err** - provides information on possible errors in the computation of proper elements
- **vprs.out** - additional numerical data on the computation of proper elements
- **vprs.pro** - proper orbital elements
- **vprs.sig** - standard deviations of proper elements residuals
- **vprs.del** - maximum deviation of each element from the computed value

Format of the **vprs.pro** files containing proper elements:

- Column 1: Asteroid number/designation
- Column 2: Proper semi-major axis [au]
- Column 3: Proper eccentricity
- Column 4: Sine of proper inclination
- Column 5: Proper frequency of mean motion [deg/yr]
- Column 6: Proper frequency of perihelion longitude [arcsec/yr]
- Column 7: Proper frequency of nodal longitude [arcsec/yr]
- Column 8: Maximum Lyapunov exponent

Important note: ORBIT9 and PROPSYNTH are UNIX executable files. They should work on MAC, but cannot be used on machines running WINDOWS operating systems!