REWORK OF THE ERA SOFTWARE SYSTEM: ERA-8

D.A. PAVLOV, V.I. SKRIPNICHENKO
Institute of Applied Astronomy RAS
nab. Kutuzova 10, St. Petersburg 191187, Russia
e-mail: dpavlov@ipa.nw.ru

ABSTRACT. The software system that has been powering many products of the IAA during decades has undergone a major rework. ERA has capabilities for: processing tables of observations of different kinds, fitting parameters to observations, integrating equations of motion of the Solar system bodies. ERA comprises a domain-specific language called SLON, tailored for astronomical tasks. SLON provides a convenient syntax for reductions of observations, choosing of IAU standards to use, applying rules for filtering observations or selecting parameters for fitting. Also, ERA includes a table editor and a graph plotter. ERA-8 has a number of improvements over previous versions such as: integration of the Solar system and TT − TDB with arbitrary number of asteroids; option to use different ephemeris (including DE and INPOP); integrator with 80-bit floating point. The code of ERA-8 has been completely rewritten from Pascal to C (for numerical computations) and Racket (for running SLON programs and managing data). ERA-8 is portable across major operating systems. The format of tables in ERA-8 is based on SQLite. The SPICE format has been chosen as the main format for ephemeris in ERA-8.

1. INTRODUCTION

This paper describes a rework of a software system ERA that has been in usage and constant development for at least 25 years (Krasinsky et al., 1989; Krasinsky, Vasilyev, 1997; Krasinsky, Vasilyev, 2006). ERA stands for "Ephemeris Research in Astronomy". Its main applications are: production of the fundamental ephemeris of the Solar System bodies EPM (Pitjeva, Pitjev, 2014); numerical motion theories of natural satellites (Poroshina et al., 2013); astronomical yearbooks (Glebova et al., 2013); various fundamental research related to the dynamics of the Solar System (Pitjeva, Pitjev, 2013).

The core of the ERA system is the implementation of a domain-specific language called SLON. Most tasks that are being done within the system are put in the form of a program code in the SLON language. Most astronomical data (observations, parameters of models, etc) is being kept in the form of tables.

The main objective of the rework was keeping the existing abilities (most notably, ability to run a lot of existing SLON programs and read existing tables) while improving the portability, manageability, stability, scalability, and extensibility of the system. Also, some new functionality was added during the process.

2. BRIEF DESCRIPTION OF THE SYSTEM

The system can be presented as consisting of two parts: the scientific part and the technical part.

The scientific part is the following set of astronomical algorithms, exposed to the user as native constructs of the SLON language:

– Reductions of astronomical observations (optical, radar ranging, laser ranging). That includes implementation of IERS Conventions (2010) for: precession and nutation models, IERS EOP corrections, solid tide models, tectonic plate models, tropospheric delay models, relativistic corrections, and other models;

– Analytical theories for satellites of outer planets and rotation of Mars; coefficients of gravitational potential of Earth, Moon and planets, other known models of Solar system bodies;

– Gauss-Everhart numerical integrator. Reworked implementation is based on (Avdyushev, 2010);

– Equations of forces for integrating the motion of: asteroids, satellite systems, whole Solar system including lunar libration (Vasilyev, Yagudina, 2014);

– Calculation of partial derivatives of astronomical observables with respect to different parameters, such as: orbital elements of Earth or observed body, station coordinates, initial position and libration angles (for Moon), rotation parameters (for Mars), solar corona parameters, masses of perturbing bodies, and many others;

– Weighted least squares method for determining the corrections to the parameters.

The technical part consists of the following components, merged into an integrated environment:
– SLON language parser and interpreter (compiler in the reworked implementation);
– Text editor for the SLON programs;
– Graph plotter;
– Access to numerical theories of celestial bodies presented in the form of Chebyshev expansions;
– Math library;
– Viewer and editor of tables with special support for astronomical data.

3. REWORK OF THE SYSTEM

Change of programming platform. Previous versions of the system were implemented almost entirely in Pascal, with limited usage of some in-house languages for system configuration. With long-term plans of making the system workable on different hardware and software environments, a different programming language and platform has to be chosen. The choice was: C for intense numerical work; Racket (`http://racket-lang.org`) for parsing and compiling SLON programs, dealing with input and output data, and building a graphical user interface.

Racket is a programming language and an open-source platform with reach feature set:
– automatic memory management with a garbage collector;
– high-performance virtual machine (VM) with Just-in-time (JIT) compiler to native code;
– portability over all variants of Windows, Linux, and Mac, including cross-platform graphic widgets;
– support for imperative, functional, and object-oriented programming styles;
– sophisticated packaging and documenting system;
– foreign function interface to C modules;
– support of Unicode, threading, extended precision (80-bit) arithmetics, Web development;
– (important for scientific programming) interactive mode, graph plotter;
– decent documentation and strong community.

In addition, Racket has arguably the most advanced macro system and other tools for creation of domain-specific languages (DSLs). While SLON is a quite complicated DSL, it was not a problem to write a parser that translate SLON constructs into Racket's syntax objects, thus making SLON language native to Racket VM, and taking full advantage of the VM's facilities, including the JIT compiler.

Transition to Racket resulted in a significant shrink of ERA's code base. Memory manager written in Pascal in 1980-s, with Soviet BESM-6 hardware in mind, is gone and superseded by Racket's generational garbage collector "3m". Custom parser generator, created for ERA around the same time, is replaced with Racket's implementation of `lex` and `yacc`. ERA's graph plotting module has been substituted by Racket's `plot` library. Finally, there was no need to reimplement an IDE for SLON in ERA-8: any domain-specific language implemented in Racket becomes native to Racket's IDE, DrRacket. Users are able to edit, compile, run, and even debug SLON programs in DrRacket directly.

Finally, automatic memory management allowed to revoke some limits for input data, inherent to previous versions of the ERA system: number of simultaneously integrated bodies, number of attributes size of SLON programs, number of arguments to SLON actors, etc.

Format of table data files. SQLite (`http://sqlite.org`) format has been chosen for storing the tabular data in ERA-8, instead of some custom binary format with custom program interface for access. SQLite library took the responsibility for disk I/O, simultaneous access, and caching of input and output data of the system. Old format is supported in ERA-8 in read-only mode.

Format of ephemeris data files. In previous versions of ERA, a special binary format was developed to store and distribute the numerical theories. ERA-8, though, has switched to another format (Hilton et al., 2014) known as the format used by the SPICE library of NASA NAIF. That format (actually, two formats used to store differend kinds of data: SPK and PCK) has been recently accepted as the main format for fundamental ephemeris among the producers (IAA RAS, NAS JPL, IMCCE). Some extensions were made to guarantee lossless conversion of IAA ephemeris to the new format. Old format is still supported in ERA-8 for backward compatibility.

4. NEW RESULTS OBTAINED WITH ERA-8

TT − TDB integration. The revocation of limit on the number of simultaneously integrated objects allowed to integrate TT − TDB difference in ERA-8 with arbitrary number of bodies. Currently, 322 most massive asteroids are accounted for in the integration of TT − TDB in ERA-8 (together with the Sun, the Moon and all the planets). The equations of integration were taken from (Klioner et al., 2010). The resulting TT − TDB differences are available in the form of an SPK file as part of EPM2011 ephemeris and are close to DE430. Figure 1 shows the difference between EPM2011 TT − TDB and DE430 TT − TDB in nanoseconds over a timespan of 400 years.

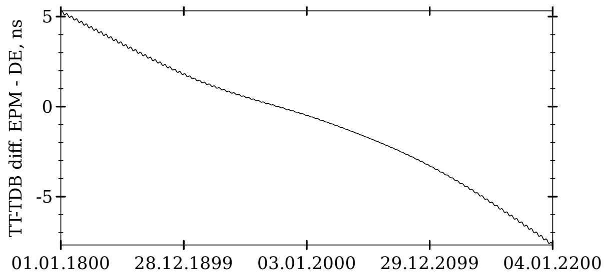

Figure 1: Difference of TT − TDB between EPM2011 and DE430, years 1800–2200.

Cassini range measurements. New Cassini ranging data available from NASA JPL (Hees et al., 2014) made it possible to improve the orbital parameters of Saturn significantly. Figure 2 shows the initial two-way O-C (obtained with EPM2011) for Cassini ranging measurements and residual errors. The RMS for the two-way residuals is about 40 m.

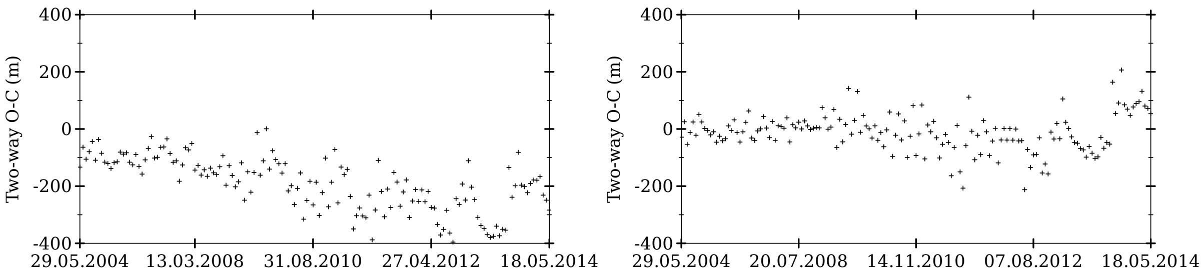

Figure 2: O-C for Cassini measurements before the corrections to Saturn orbit (left) and after (right).

Improvement of the orbit of Pluto. Processing of some observations of Pluto not used previously in the EPM ephemeris was done with ERA-8. More than 8000 observations have been processed, and that resulted into the standard deviations of orbital parameters of Pluto reduced roughly in half. See (Girdiuk, 2015) for the description of this work.

Web site for ephemeris access. Racket platform and its rich libraries for Web development have allowed to expose a piece of ERA-8 facilities as a website (`http://ephemeris.ipa.nw.ru`). The website allows users to calculate ephemeris tables for Sun, Moon, planets, and natural satellites. A number of options is available for: choosing the coordinate system (equatorial, ecliptical, horizontal); choosing the equator (mean J2000, mean of the date, true of the date); choosing the type of the coordinates (Cartesian or spherical); specifying the location of the observer; formatting the output data. The users are also free to choose the planetary theory (EPM, DE, INPOP in different versions) and the theory for natural satellites. All the ephemeris data used by the site is stored as SPICE files.

5. CONCLUSION AND PLANS FOR NEAR FUTURE

ERA-8 has moved to a more advanced software platform while keeping backward compatibility to the previous versions of ERA. Also, the system took a step to new environments, such as Linux desktops and web servers. The program code has become more transparent, manageable, and flexible, and as a result, new features can be added more quickly.

ERA-8 will definitely benefit from embracing the SOFA library (`http://iausofa.org`) as the implementation of the IERS Conventions (2010). SOFA is to be included into ERA-8 in early 2015.

The next version of the EPM ephemeris—EPM2014—is being prepared with ERA-8, and so is the next issue of the Astronomical Yearbook (2016).

In 2015, ERA-8 will be freely available to users (as WinERA currently is) from the IAA's web site.

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