Rework of the ERA software system: ERA-8

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ERA: Ephemeris Research in Astronomy

- Optical observations
- Radar ranging observations
- Laser ranging observations
- Other observations

Models for solar system dynamics and reductions of observations

EPM (Ephemerides of Planets and Moon)

Fundamental research related to the Solar System

Astronomical Yearbook etc.

Web access
Components of ERA

Integrated development environment (IDE): text editor, debugger, interactive prompt, graph plotter

Core ERA system

Table-organized observations and other data (SQLite)

Programs in SLON (domain-specific language)

Ephemeris data (Chebyshev expansions, SPICE)

Command-line interface for batch programs
Features of ERA

- **System part**
  - Compiler and IDE for the SLON language
  - Access to tabular astronomical data stored in plain text or internal binary formats
  - Math library including 80-bit extended precision floating point numbers

- **Scientific part**
  - Precession and nutation models, EOP, solid earth tides, plate motion
  - Time transformations, atmospheric refraction, relativistic effects
  - Models of natural satellites (TASS, GUST, etc) and rotation of planets
  - Numerical integrator by Gauss-Everhart algorithm (Avdushev, 2006)
  - Equations of solar system dynamics for: planets, Sun, Moon, lunar libration, minor planets, spacecraft, natural satellites, TT-TDB
  - Calculation of residuals (O-C) and partials by observations: optical, radar ranging, LLR, SLR, pseudorange, VLBI
  - Refinement of initial parameters and constants via the LSM
What has been reworked in ERA-8

- Source code rewritten from Pascal to: C for intensive calculations; Racket for logic, SLON language parser/compiler, and the GUI
- Racket’s IDE DrRacket serves as IDE for ERA-8
- Portable across Windows/Linux, 32- and 64-bit
- Improved stability and diagnostics, revoked legacy limitations
- Table storage format has been changed to SQLite
- SLON language improved (new syntactic features, easier configuration)
- Acceptance of the international ephemeris file formats SPK (independent libraries for access: JPL SPICE, IMCCE Calceph)
- Unified access to all major ephemerides: EPM (IAA), DE (JPL), and INPOP (IMCCE)

Why Racket?

- Flexible programming language (dynamic typing, garbage collector, most advanced macro system, JIT compiler, interfacing to/from C)
- Most advanced tools for DSL creation
- Cross-platform
- Open-source (allowed us to implement 80-bit arithmetics, now in upstream)
Examples of ERA applications

1. Correction of the orbit of Saturn by fitting to Cassini range measurements (2004-2014)
   see slides 7-13

2. Checking the precision of the numerical integrator
   see slides 14-16
Cassini ranging: reading DSN stations

SQLite table of stations
Cassini ranging: reading observations

SQLite table of range data

Cassini ranging: O-C and partials

Already adjusted to the delay due to: solar plasma, Earth troposphere and ionosphere, and spacecraft transponder. Reductions made to account for: light delay, time transformations.

SQLite table of residuals and partials
Calculating corrections and formal errors for the six Lagrangian elements of Saturn

SQLite table of corrections
Cassini ranging: applying the corrections

coordinates → elements;
apply corrections to the elements;
refined elements → refined coordinates.

New initial vector
Cassini residuals (before correction)

Date

Two-way residual (m)

N = 196
Cassini residuals (final)

source: Elena Pitjeva, “Evolution of ephemerides EPM of IAA RAS”
Idea:

1. run the numerical integration for the timespan of 400 years;
2. save the state vector in the end;
3. run the numerical integration 400 years back (to the initial date);
4. calculate the difference between the resulting ephemeris (should be zero mathematically, non-zero difference gives an estimate of the integrator precision).
Results of two-way integration: Mercury

double precision

extended precision
Results of two-way integration: Moon

double precision

extended precision
Future plans

- Incorporation of the modern software libraries into ERA:
  - SOFA library
  - Numerical libraries?
- Incorporation of the newest models of solar system bodies:
  - GRACE (Earth gravitational potential)
  - GRAILS (Lunar gravitational potential)
- Release of EPM2014 ephemerides
- Extensibility for the users
- Public release with user documentation, including description of all underlying algorithms and reductions

For now:
- ftp://quasar.ipa.nw.ru/incoming/EPM/ (EPM2011m ephemeris files)
- http://ephemeris.ipa.nw.ru/ (interactive ephemerides calculation)

Thank you for your attention
Backup slides
Cassini range measurements

1. Read x/y/z positions and yearly trends of stations of the Deep Station Network
2. Read observations: UTC date, round trip time, position of the spacecraft w.r.t. Saturn system barycenter
3. Calculate residuals (O-C) and their partials w.r.t. Lagrangian orbital elements of Earth and Saturn on epoch $T_0$
4. Put the residuals and partials into a system of conditional equations
5. Solve the system with LSM, get the corrections for orbital elements
6. Apply the corrections
7. Re-integrate the Solar system in the time span from $T_0$ to observations’ time
8. Repeat from step 3 until the residuals stabilize.