Rework of the ERA software system: ERA-8

D. Pavlov, V. Skripnichenko
Institute of Applied Astronomy RAS

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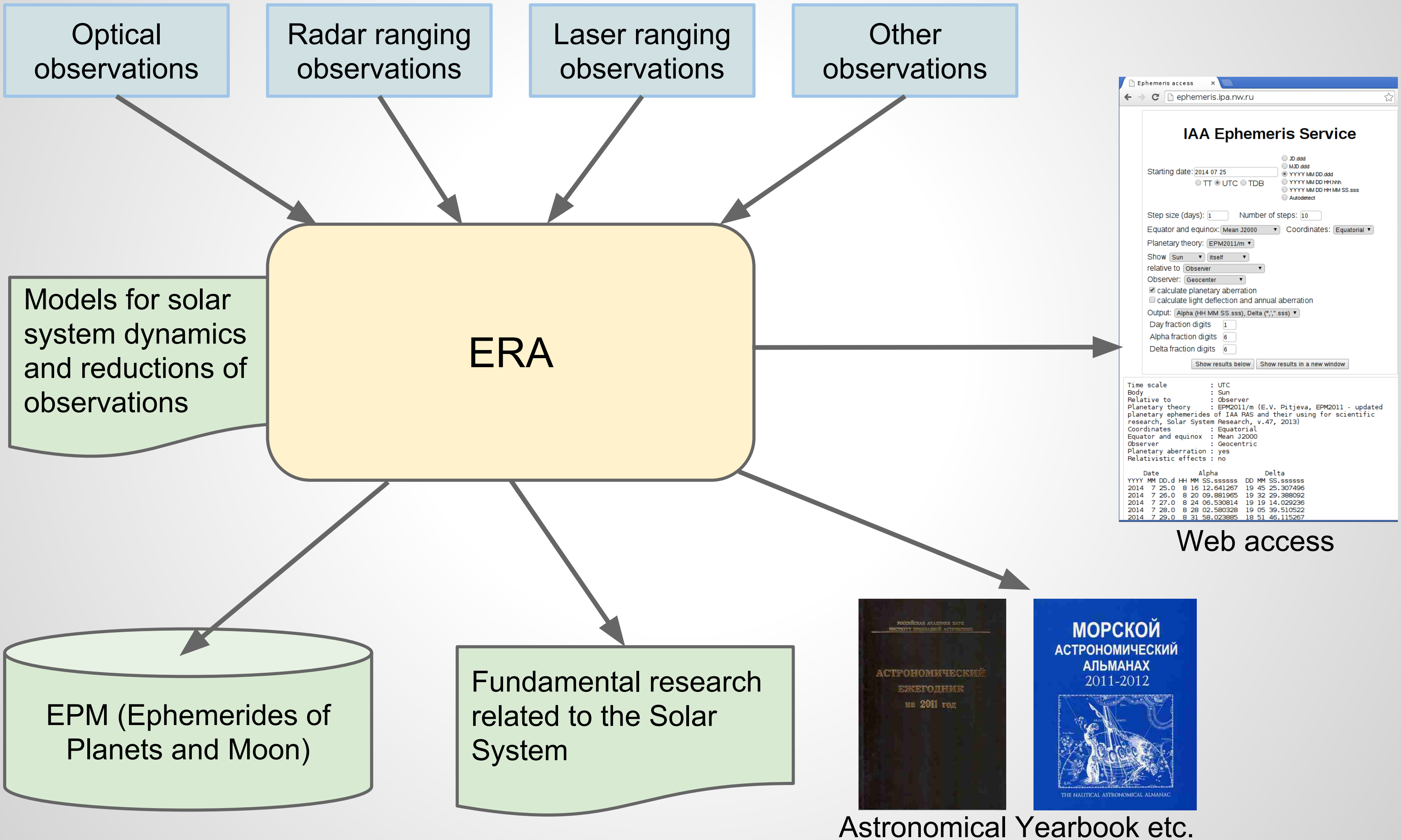
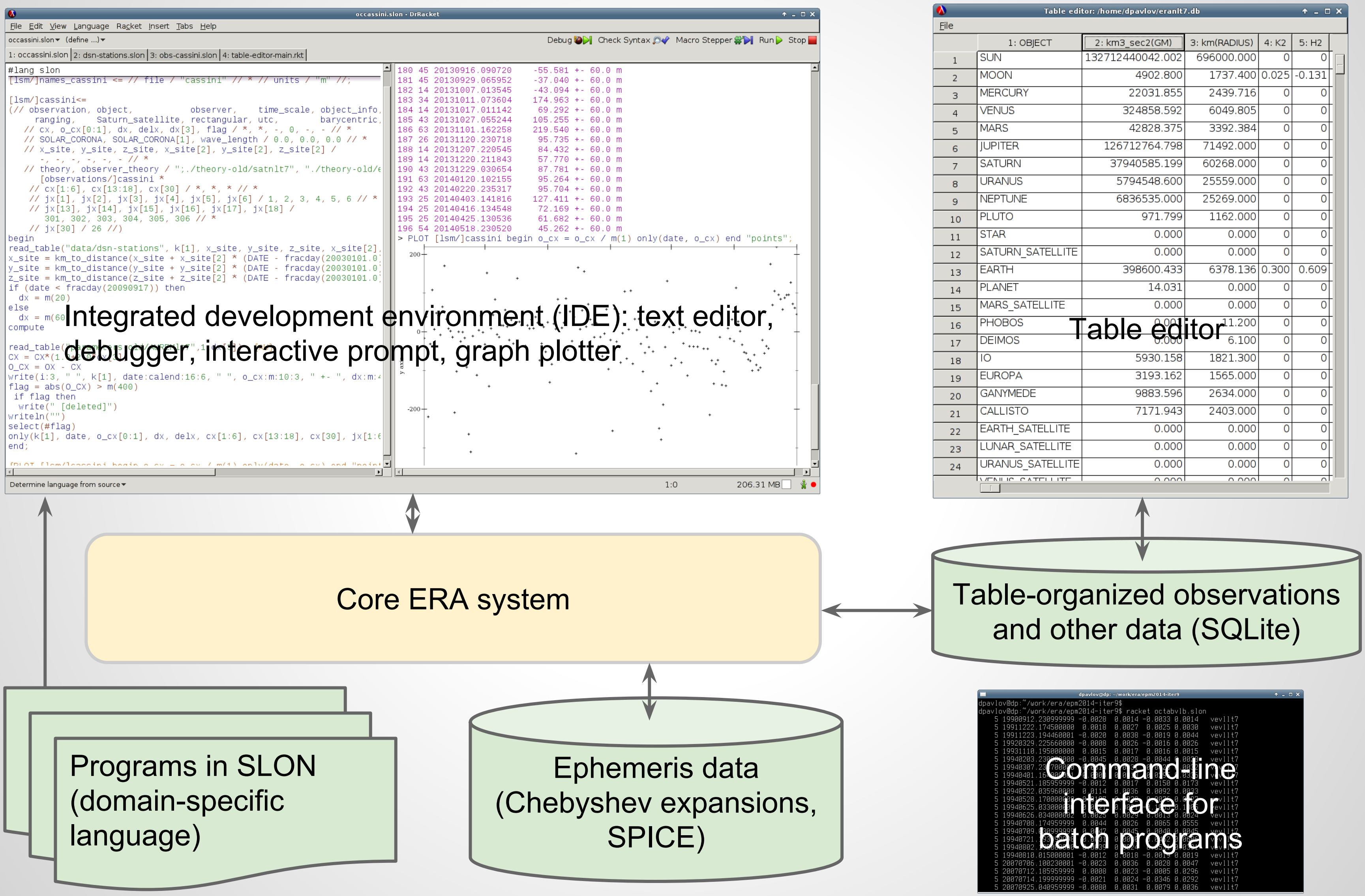
ERA: Ephemeris Research in Astronomy



Components of ERA



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

iau-comm4.jpl.nasa.gov/plan-eph-data/stations27oct2008.html

DSN STATION COORDINATES

Station locations used for planetary spacecraft tracking,
with identifying numbers assigned by the NASA Deep Space Network.

Locations are in ITRF 2005 reference frame at epoch 2003.0.

##	x(m)	y(m)	z(m)	vx(m/yr)	vy(m/yr)	vz(m/yr)
11	-2351429.1573	-4645078.8462	3673764.1469	-0.017	0.005	-0.005
12*	-2350442.8774	-4651978.5701	3665629.1568	-0.017	0.005	-0.005
12	-2350443.9994	-4651980.7901	3665630.9178	-0.017	0.005	-0.005
13	-2351112.6524	-4655530.6640	3660912.7137	-0.017	0.005	-0.005
14	-2353621.3873	-4641341.4492	3677052.2629	-0.017	0.005	-0.005
15	-2353538.9453	-4641649.4462	3676669.9609	-0.017	0.005	-0.005
16	-2354763.3193	-4646787.4121	3669386.9959	-0.017	0.005	-0.005
17	-2354730.5183	-4646751.7261	3669440.5859	-0.017	0.005	-0.005
23	-2354757.7273	-4646934.6251	3669207.7509	-0.017	0.005	-0.005
24	-2354906.7043	-4646840.1231	3669242.3109	-0.017	0.005	-0.005
25	-2355022.0073	-4646953.2321	3669040.5529	-0.017	0.005	-0.005
26	-2354890.7903	-4647166.3561	3668871.7409	-0.017	0.005	-0.005
27	-2349915.4204	-4656756.4340	3660096.4547	-0.017	0.005	-0.005
28	-2350102.0104	-4656673.3970	3660103.5037	-0.017	0.005	-0.005
33	-4461083.8842	2682281.7581	-3674569.9078	-0.035	0.000	0.045
34	-4461147.1342	2682439.3011	-3674393.0678	-0.035	0.000	0.045
41	-3978720.5639	3724850.9534	-3302171.0387	-0.034	0.000	0.045
42	-4460981.3872	2682413.5301	-3674581.5878	-0.035	0.000	0.045
43	-4460894.9092	2682361.5401	-3674748.0458	-0.035	0.000	0.045
44	-4451074.3413	2676823.9203	-3691346.7139	-0.035	0.000	0.045
45	-4460935.6092	2682765.7171	-3674380.9088	-0.035	0.000	0.045
46	-4460828.9882	2682129.5691	-3674975.0228	-0.035	0.000	0.045
49	-4554232.2327	2816758.9761	-3454035.5754	-0.035	0.000	0.045
53	4849330.0413	-360337.9005	4114758.8930	-0.007	0.019	0.011
54	4849434.5133	-360723.9325	4114618.8160	-0.007	0.019	0.011
55	4849525.2813	-360606.1255	4114495.0650	-0.007	0.019	0.011

dsn-stations.slon - DrRacket

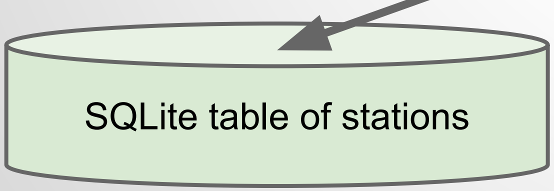
File Edit View Language Racket Insert Tabs Help

dsn-stations.slon (define ...) Debug Check Syntax Macro Stepper Run Stop

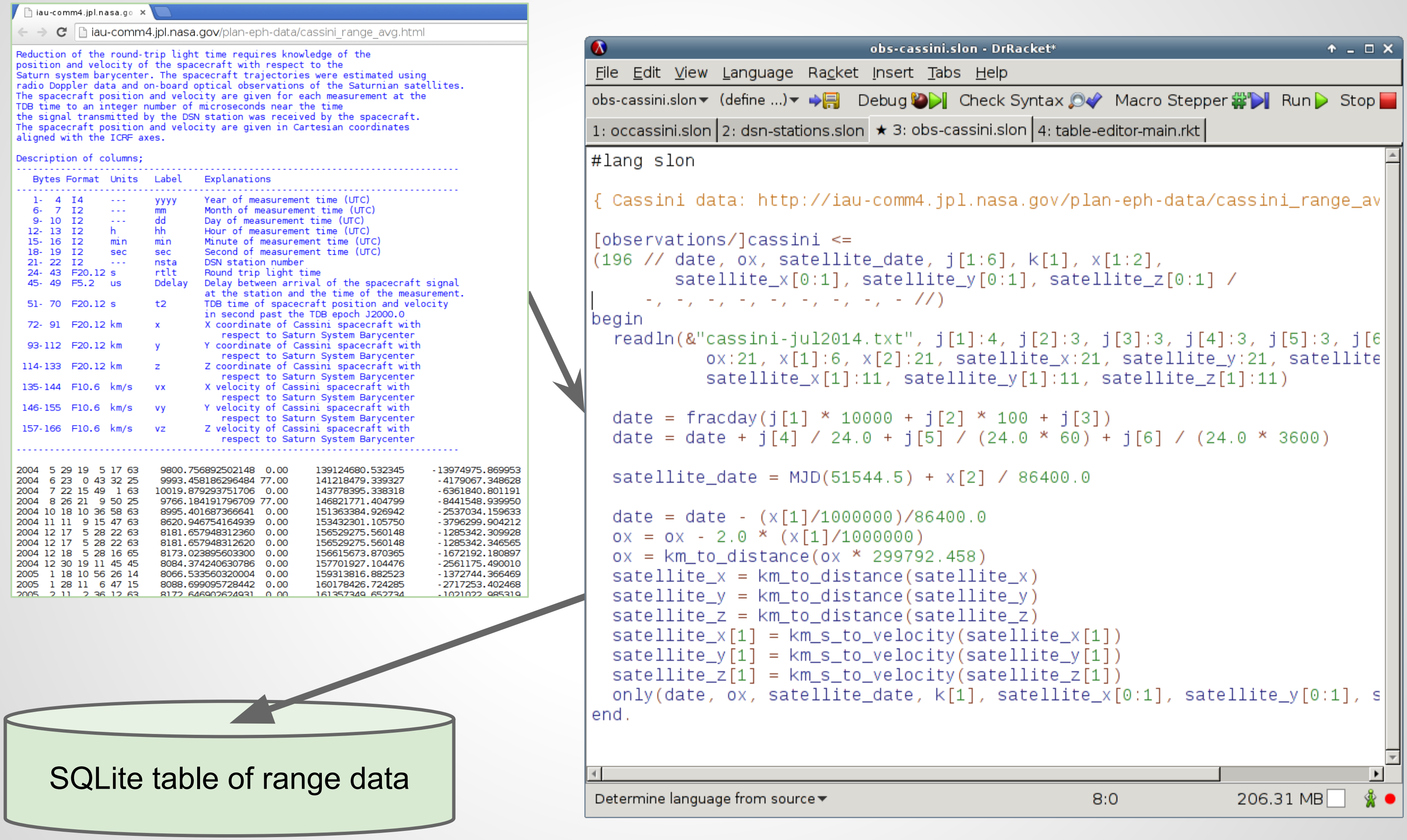
1: occassini.slon | 2: dsn-stations.slon | 3: obs-cassini.slon | 4: table-editor-main.rkt

```
#lang slon
:= // name, k, k[1], site, x_site, y_site, z_site, x_site[2], y_site[2], z_site[2],
                                 x_site[1], y_site[1], z_site[1], x_site[3], y_site[3], z_site[3]
   / "dsn_stations.txt", -, -, -, -, -, -, -, -, -, -, -, -, -, -, -//
begin
  k = 0
  repeat
    x_site[1] = 0
    y_site[1] = 0
    z_site[1] = 0
    x_site[3] = 0
    y_site[3] = 0
    z_site[3] = 0
    readln(&name, k[1]:2, site:1, x_site[1]:14, y_site[1]:15, z_site[1]:15,
                                       x_site[3]:8, y_site[3]:8, z_site[3]:8)
    if site <> "*" then begin
      writeln(k[1], " ", site)
      if k[1] > k + 1 then
      repeat
        k = k + 1
        x_site = 0
        y_site = 0
        z_site = 0
        x_site[2] = 0
        y_site[2] = 0
        z_site[2] = 0
        append_table("data/dsn-stations",
                      x_site, y_site, z_site, x_site[2], y_site[2], z_site[2])
      until k[1] = k + 1
      k = k[1]
      x_site = x_site[1] / 1000.0
      y_site = y_site[1] / 1000.0
      z_site = z_site[1] / 1000.0
      x_site[2] = x_site[3] / (1000.0 * 365.25)
      y_site[2] = y_site[3] / (1000.0 * 365.25)
      z_site[2] = z_site[3] / (1000.0 * 365.25)
      append_table("data/dsn-stations",
                    x_site, y_site, z_site, x_site[2], y_site[2], z_site[2])
    end
  until eof(name)
end.
```

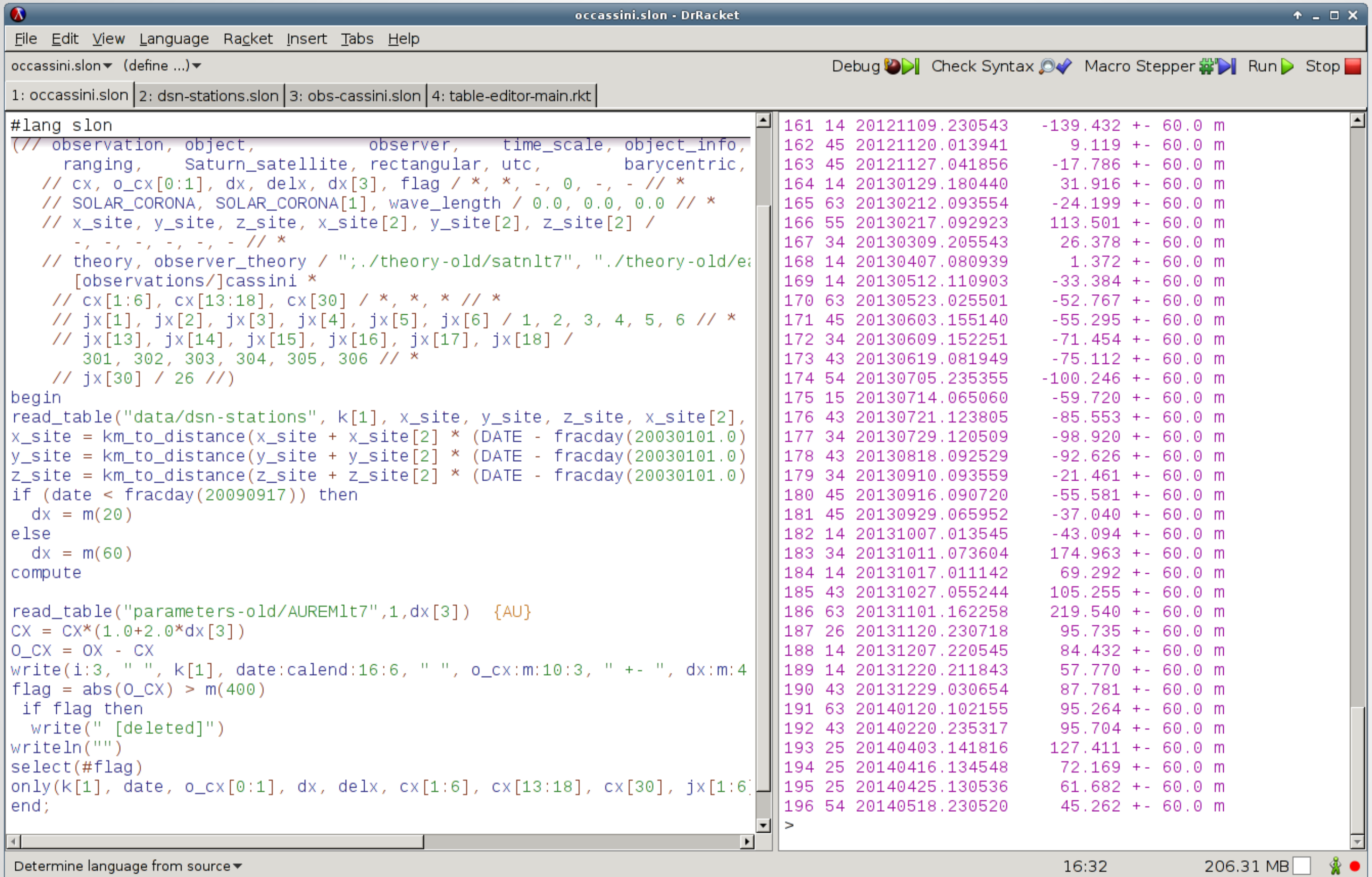
Determine language from source 1:0 206.31 MB



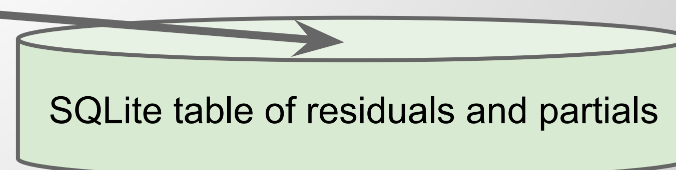
Cassini ranging: reading observations



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.



Cassini ranging: LSM

allnlt7_lsm.slon - DrRacket

File Edit View Language Racket Insert Tabs Help

allnlt7_lsm.slon (define ...) Debug Check Syntax Macro Stepper Run Stop

1: occassini.slon | 2: dsn-stations.slon | 3: obs-cassini.slon | 4: table-editor-main.rkt | 5: allnlt7_conv.slon | 6: allnlt7_lsm.slon

```
#lang slon
params_u4 := // n / 265 / 266 / 267 / 268 / 269 / 270 //;
params_n1 := // n / 271 / 272 / 273 / 274 / 275 / 276 //;

[lsm/]params <= ;
[lsm/]params <= (params_earth +
                 params_mars + params_mars_ext +
                 params_vik1  + params_vik2 + params_pfnd + params_odys +
                 params_venus +
                 params_mercury + params_mercury_legendre +
                 params_jupiter + params_j1 + params_j2 + params_j3 + params_j4 +
                 params_saturn + params_s3 + params_s4 + params_s5 + params_s6 + params_s7 + params_s8 + params_s9 +
                 params_uranus + params_u1 + params_u2 + params_u3 + params_u4 +
                 params_neptune + params_n1  +
                 params_pluto +
                 params_masses +
                 params_corona +
                 params_common
                 ) * // dx[0:1] / - //;
:= // iterations,n_sigma / 3, 3 //
begin
lsm_processor("lsm/names","lsm/params","lsm/corr","lsm/rms")
end;

:= [lsm/]names
begin
  writeln(&"result.txt", "File ", file:8, " before solving", "       File ", file:8, " after solving")
  writeln(&"result.txt", "  first parameter (" + units + ")")
  if units = "arcs" then begin
    writeln(&"result.txt", "    A   = ", mean_o_c[0]:arcs:13:6,     "            A   = ", mean_o_c[1]:arcs:13:6)
    writeln(&"result.txt", "    DA  = ", d_mean_o_c[0]:arcs:13:6,   "            DA  = ", d_mean_o_c[1]:arcs:13:6)
    writeln(&"result.txt", "    RMS = ", rms[0]:arcs:13:6,          "            RMS = ", rms[1]:arcs:13:6)
  end else begin if units = "m" then begin
    writeln(&"result.txt", "    A   = ", mean_o_c[0]:m:13:6,     "            A   = ", mean_o_c[1]:m:13:6)
    writeln(&"result.txt", "    DA  = ", d_mean_o_c[0]:m:13:6,   "            DA  = ", d_mean_o_c[1]:m:13:6)
    writeln(&"result.txt", "    RMS = ", rms[0]:m:13:6,          "            RMS = ", rms[1]:m:13:6)
  end else begin if units = "mcs" then begin
```

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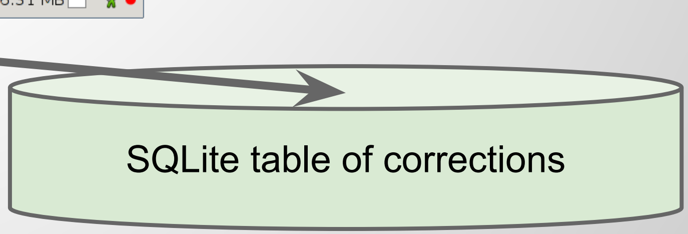
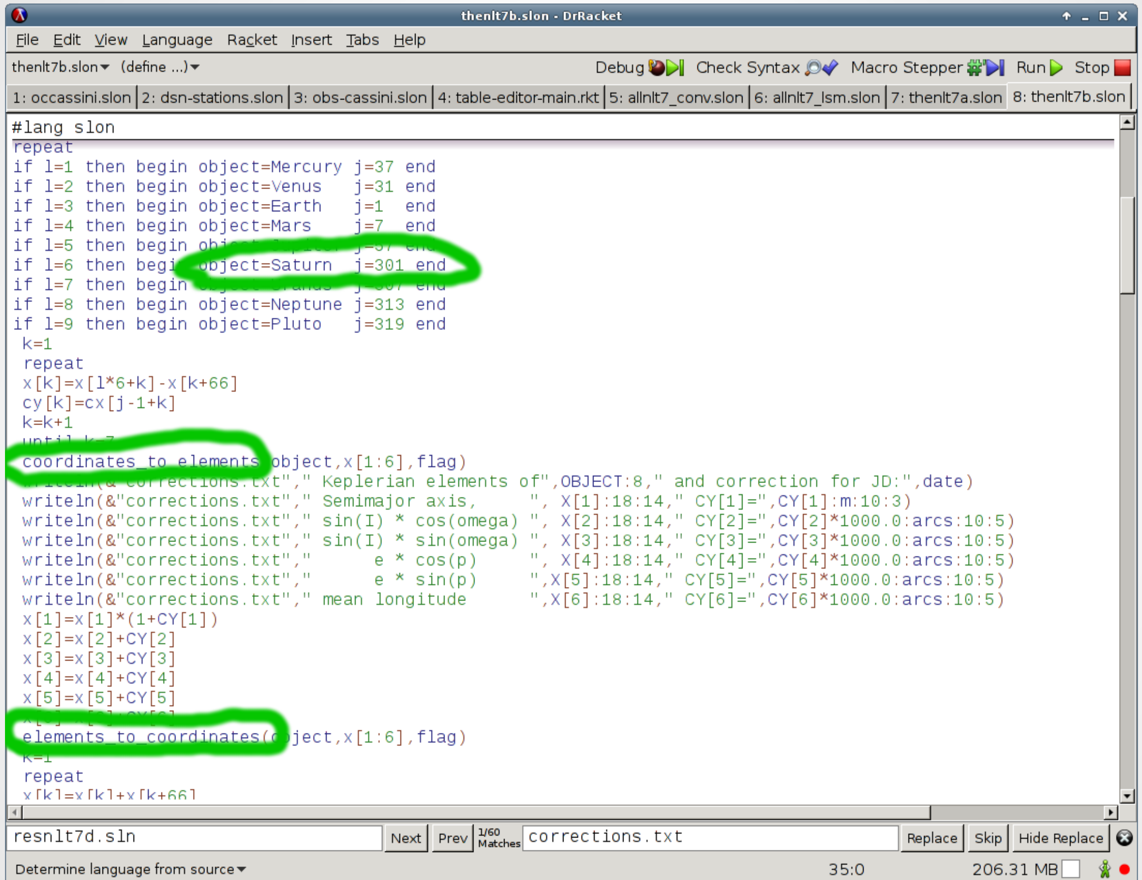
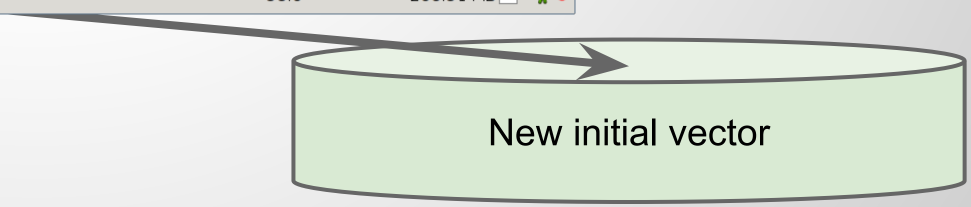


Calculating corrections and formal errors for the six Lagrangian elements of Saturn

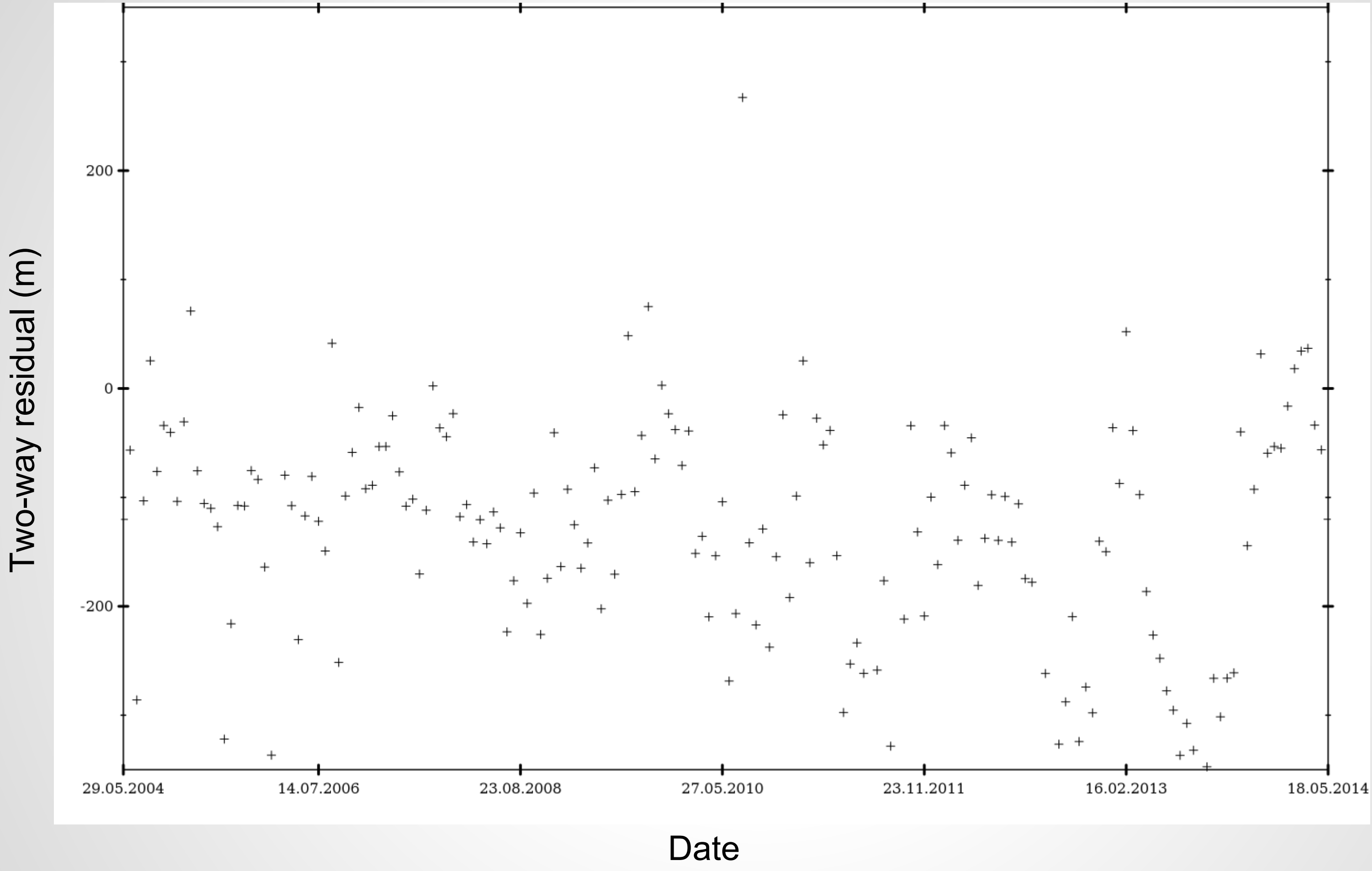
Cassini ranging: applying the corrections





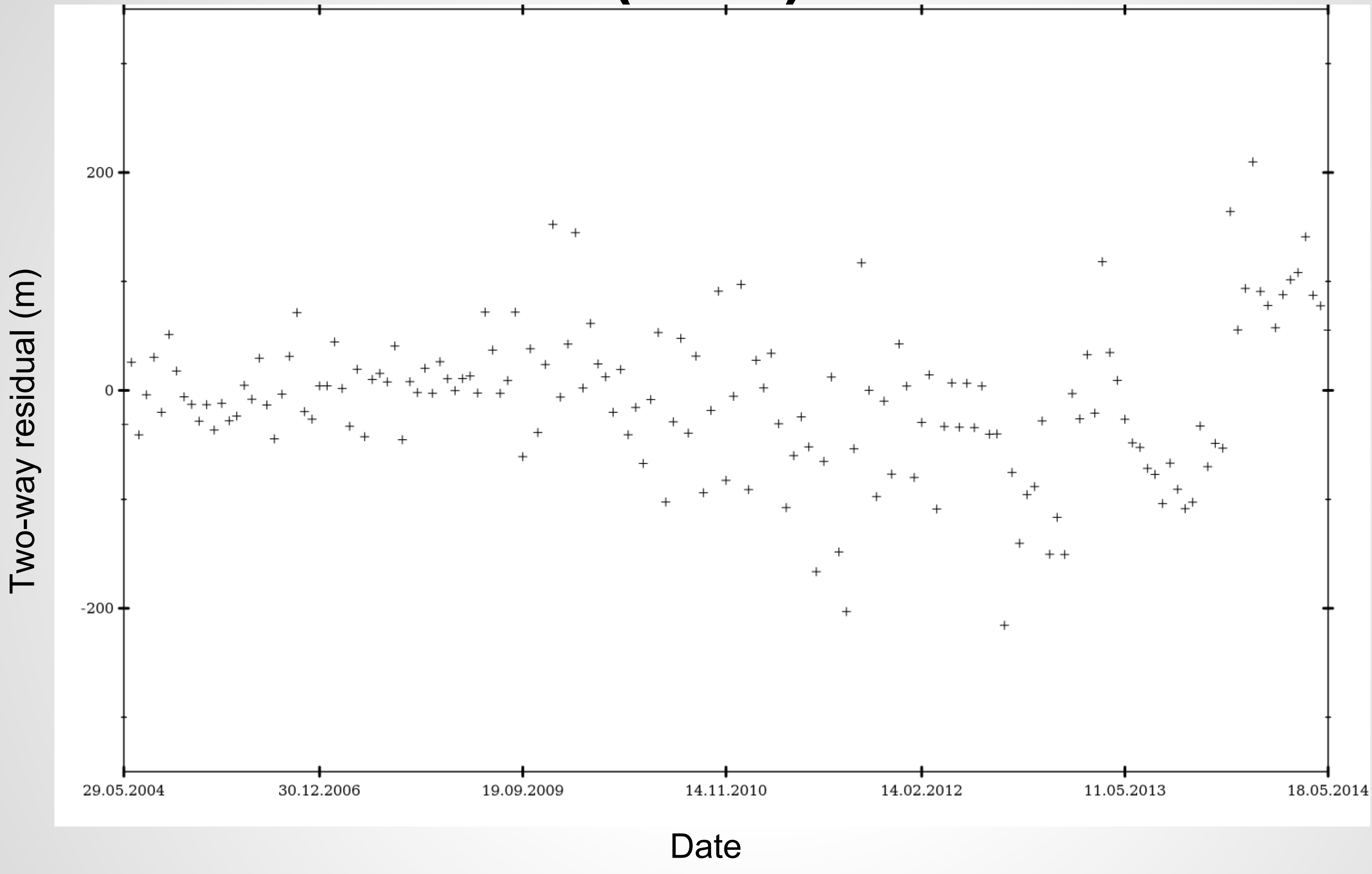
coordinates → elements;
apply corrections to the elements;
refined elements → refined coordinates.

Cassini residuals (before correction)



N = 196

Cassini residuals (final)



N = 161
RMS = 40m

Ephemeris	Planet	a [m]	$\sin i \cos \Omega$ [mas]	$\sin i \sin \Omega$ [mas]	$e \cos \pi$ [mas]	$e \sin \pi$ [mas]	λ [mas]
EPM2004	Saturn	4222	3.237	4.085	3.858	2.975	3.474
EPM2008		12.026	0.09448	0.09246	0.00161	0.00135	0.02477
EPM2011		70.519	0.10792	0.12023	0.01093	0.00327	0.03434
EPM2013		67.973	0.09517	0.10313	0.01021	0.00276	0.02885
EPM2014		4.828	0.08065	0.05726	0.00097	0.00035	0.01239

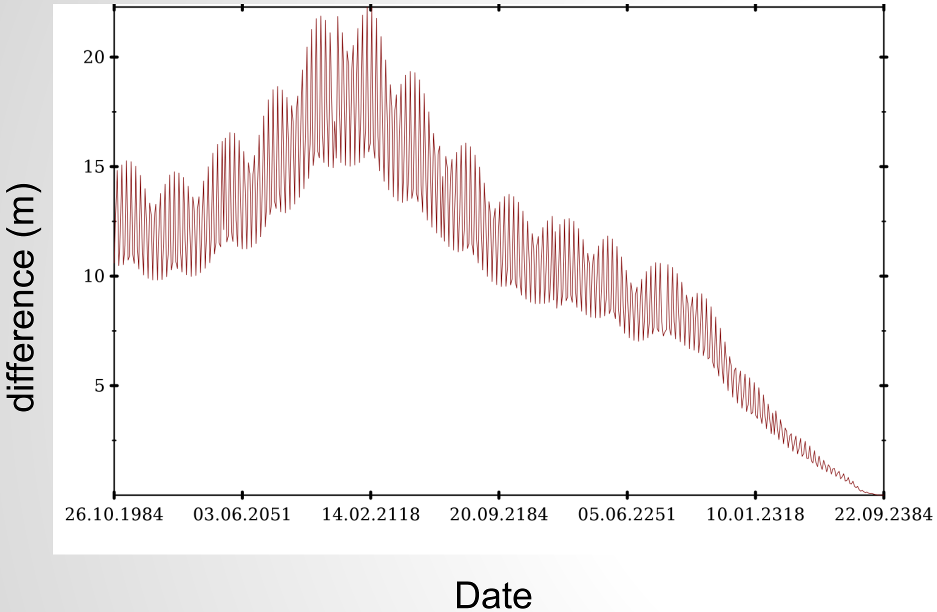
source: Elena Pitjeva, “Evolution of ephemerides EPM of IAA RAS”

Two-way integration

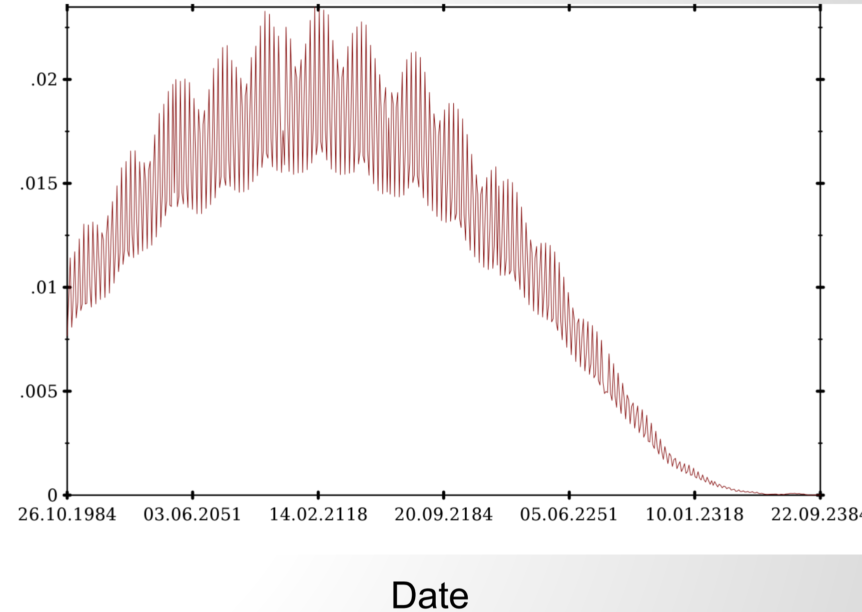
Idea:

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

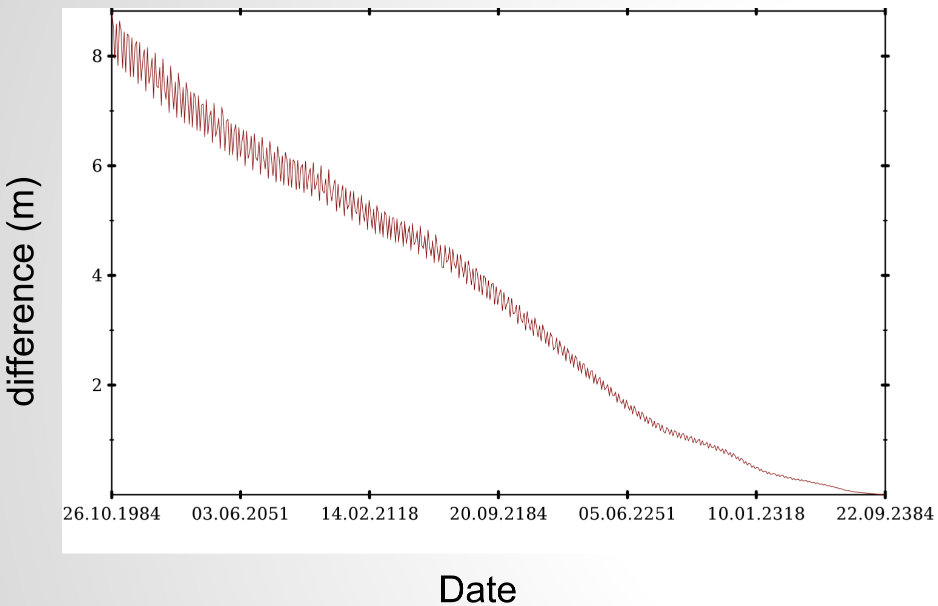


double precision

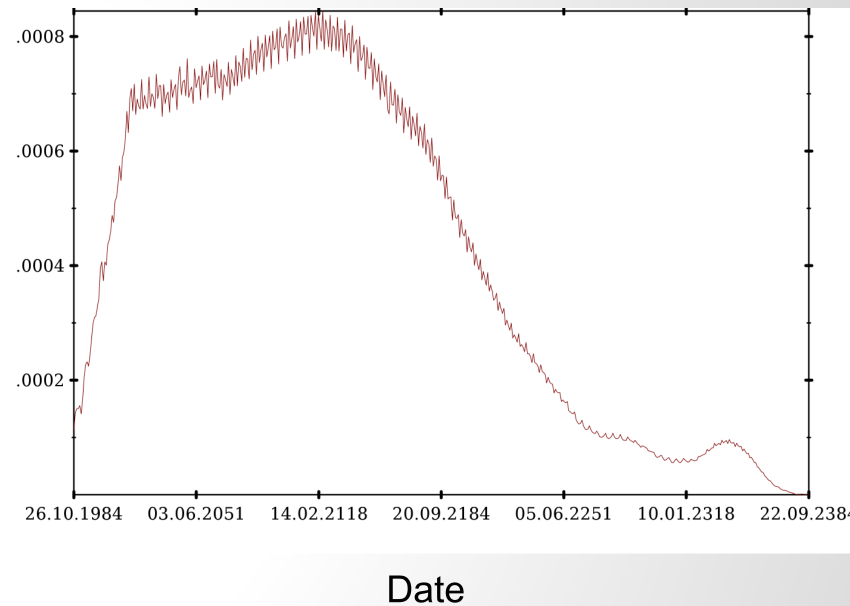


extended precision

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.