

The system of Ephemeris Research in Astronomy ERA, Ephemeris of Planets and the Moon EPM: current status and future plans

Naumov K.A., Lebedeva M.A., Yakovlev V.A., Vasilyev M.V., Yagudina E.I. and Zotov K.A.

Institute of Applied Astronomy RAS
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EPM ephemeris (Ephemeris of Planets and Moon) has been produced for more than 30 years and contains information about the position of the:

- **planets** of the Solar system
- the **Sun**
- the **Moon**
- **five asteroids** (Ceres, Pallas, Vesta, Iris, Bamberga)
- **five TNO** (Pluto, Eris, Makemake, Haumea, Sedna).

As well as **TT-TDB** and Euler angles for **lunar physical libration**.

The **ERA system** and the database of observations of Solar system bodies are used to create EPM ephemerides.

To date, several versions of EPM ephemerides have been released: EPM2004, EPM2008, EPM2011/m, EPM2015, EPM2017 and EPM2021.

ERA stands for “Ephemeris Research in Astronomy”.

Its main applications are:

- production of the fundamental ephemeris of the Solar System bodies EPM [1];
- numerical motion theories of natural satellites [2];
- astronomical yearbooks [31];
- various fundamental research related to the dynamics of the Solar System [3].

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.

ERA has been in usage and constant development since late 1980-s [4]. It has undergone a major rework in 2015.

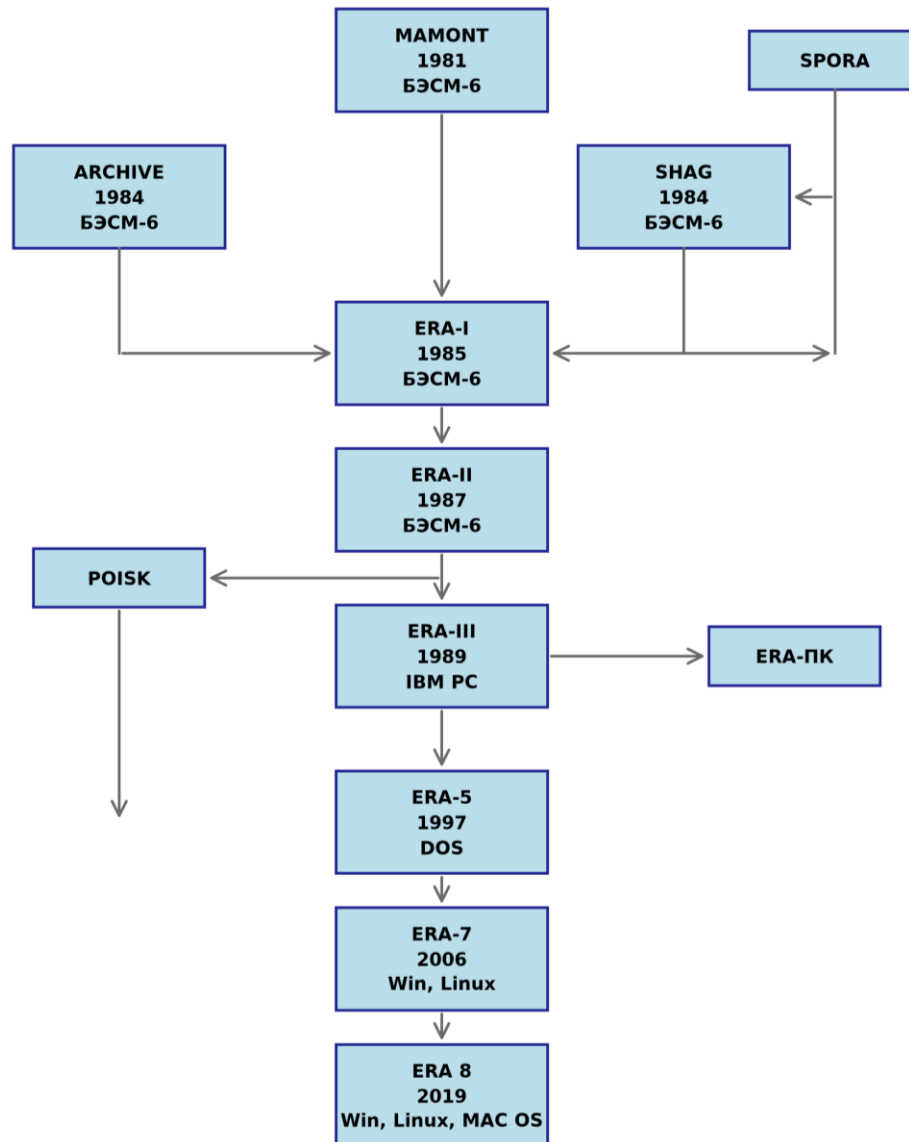
The system can be presented as consisting of two parts: the scientific part and the technical part.

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);
- 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;
- Adams–Bashforth-Moulton numerical integrator;
- Equations of forces for: asteroids, satellite systems, whole Solar system including TT-TDB and lunar libration;
- Calculation of partial derivatives of astronomical observables with respect to different parameters;
- Weighted least squares method for determining the corrections to the parameters.

The technical part consists of the following components, merged into an integrated environment based on the Racket programming platform:

- 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.



- The first significant result in this area was the MAMONT-1981 system for automating ephemeris calculations [6]. – BESM-6, first ephemerides from 1945 to 1985.
- MAMONT-1981 (Mathematical Modeling of Celestial-Mechanical Theories). The first ephemerides of all major objects in the Solar System (covering the period from the 18th to the 20th century) were based on numerical theories of the motion of these objects [7]. Limitations — it is impossible to solve an arbitrary astronomical problem.

- In 1985, G. A. Krasinsky, F. A. Novikov, and V. I. Skripnichenko developed the first experimental version of the ERA-1 system (BESM-6) and the domain-oriented programming language SLON (System for Logical Observation Processing) based on MAMONT-81 and SPORA [8,9].
- ERA-3 (Ephemeris Research in Astronomy) (DOS) [10] – contains numerous errors.
- ERA-5: Using programs written in the high-level languages SLON; including observations of planets, their satellites, small bodies of the Solar System, the Moon, artificial Earth satellites, spacecraft, VLBI observations of quasars, pulsar timing, etc.; processing high-precision numerical theories of the planets of the Solar System, the Sun and the Moon, theories of the motion of planetary satellites, small planets and comets, numerical ephemerides of navigation satellites[11].
- ERA-7: transfer to OS Windows, Linux [12].

ERA -8 was developed in 2014 [13].

The main innovations is:

- 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
- code of ERA-8 has been completely rewritten from Pascal to C (for numerical computations) and Racket (for running SLON programs and managing data)
- The SPICE format has been chosen as the main format for ephemeris

There are three different ephemeris:

- DE (JPL, USA)
- EPM (IAA RAS, Russia)
- INPOP (IMCCE, France)

The EPM ephemerides (Ephemerides of Planets and the Moon) were first created in the 1970s in support of Russian space flight missions and constantly improved at IAA RAS. Several factors influence the progress of planet ephemerides: dynamical models of planet motion; observational data, with the crucial role of spacecraft ranging with their growing accuracy; reduction of observations; updated database of asteroids (masses and orbits); program software; access to ephemerides.

EPM include high-precision ephemeris of the Sun, the Moon, eight major planets, Pluto, five asteroids (Ceres, Pallas, Vesta, Iris, Bamberga) and 4 TNO (Eris, Haumea, Makemake, Sedna), as well as TT-TDB and Euler angles for lunar physical libration.

- EPM87: Mutual perturbations from the major planets, the Sun, the Moon and 5 more massive asteroids; the relativistic perturbations [14].
- EPM98: perturbations from 300 asteroids [15].
- EPM2000: Perturbations due to the solar oblateness J_2 [16].
- EPM2004: Perturbation from the massive one-dimensional asteroid ring with the constant mass distribution [17].
- EPM2008: Perturbations from the 21 largest TNO (Trans-Neptunian Objects) [18].
- EPM2011: Perturbation from a massive ring of TNO [19].
- EPM2015: Perturbation from the two-dimensional discrete asteroid annulus and discrete TNO ring; perturbations from the 30 largest TNO [20].
- EPM2017: inclusion of the Lense–Thirring acceleration; modelling the acceleration of the Sun as a regular body; new models of the asteroid belt and the Kuiper belt [21].
- EPM2021: improved way to calculate radio signal delays in solar plasma; update in the method of determination of asteroid masses [22].

Comparison different EPMs



Planet	Ephemeris	a, m	$\sin(i)\cos(\Omega)$, mas	$\sin(i)\sin(\Omega)$, mas	λ , mas
Mercury	EPM2004	0.105	1.654	1.525	0.375
	EPM2014	0.065	0.7976	0.5545	0.1536
	EPM2021	0.019	0.00204	0.00357	0.0105
Jupiter	EPM2004	639	2.410	2.207	1.109
	EPM2014	347	2.005	1.808	0.882
	EPM2021	5	1.333	0.709	0.130
Neptune	EPM2004	478532	4.214	8.600	35.163
	EPM2014	270479	2.669	5.195	12.345
	EPM2021	6385	2.157	1.805	3.648
Pluto	EPM2004	3463309	6.899	14.940	79.089
	EPM2014	563306	0.865	3.312	4.870
	EPM2021	11537	0.727	2.438	3.739

Table 1. The formal standard deviations of planetary orbital elements adjusted in EPM2004, EPM2014 and EPM2021 ephemerides

EPM2021 (1787–2214) and EPM2021H (13199 BC — AD 17191)

Dynamical model:

- Barycentric Celestial Reference System (BCRS)
- Newtonian forces, Einstein–Infeld–Hoffmann equations, Lense–Thirring effect, accelerations from solar oblateness
- All planets, Pluto, the Moon, the Sun, 277 asteroids, the discrete uniform 180-point asteroid annulus [23], 30 TNOs, and the discrete uniform 160-point TNO ring.

Moon ephemeris:

- The Moon is modeled as an elastic body with a rotating liquid core [24].
- perturbations of the Moon's orbit in Earth's gravitational field;
- rotational torque due to the Moon's gravitational potential;
- perturbations of the Moon's orbit due to lunar and solar tides on Earth;
- distortion of the Moon's shape as a result of its rotation and Earth's gravity;
- rotational torque arising from the interaction between the lunar crust and the liquid core.

Lunar Laser Ranging



Fig.1. ILRS observatories carrying out Lunar Laser Ranging (LLR) to retro-reflector arrays on the surface of the Moon

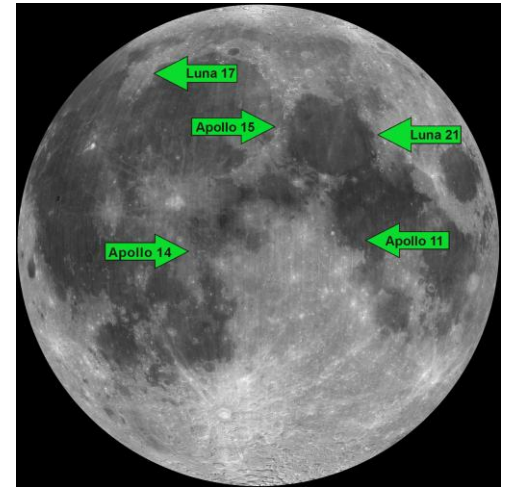


Fig. 2. Location of retroreflectors on the Moon's surface.

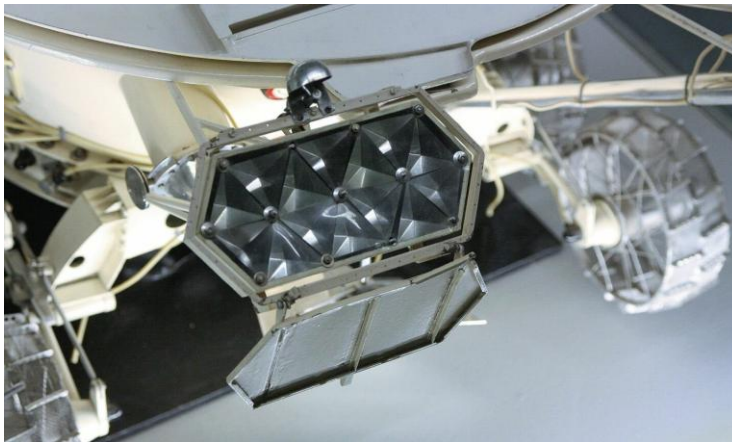


Fig.3. Lunokhod retroreflector.

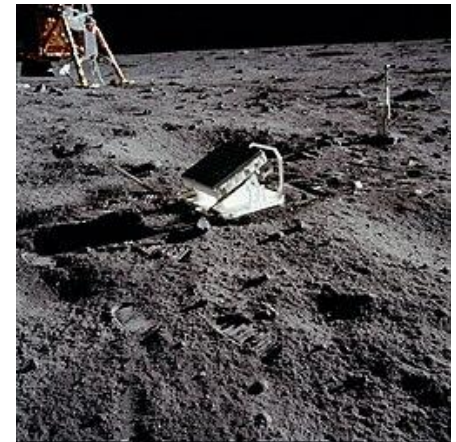


Fig.4. Apollo 11 Lunar Laser Ranging Retroreflector.

Next Generation Lunar Retroreflector-1 (NGLR-1)

- Payload of Blue Ghost M1 (2025)
- Next-generation single solid lunar Cube Corner Retroreflectors (CCRs)

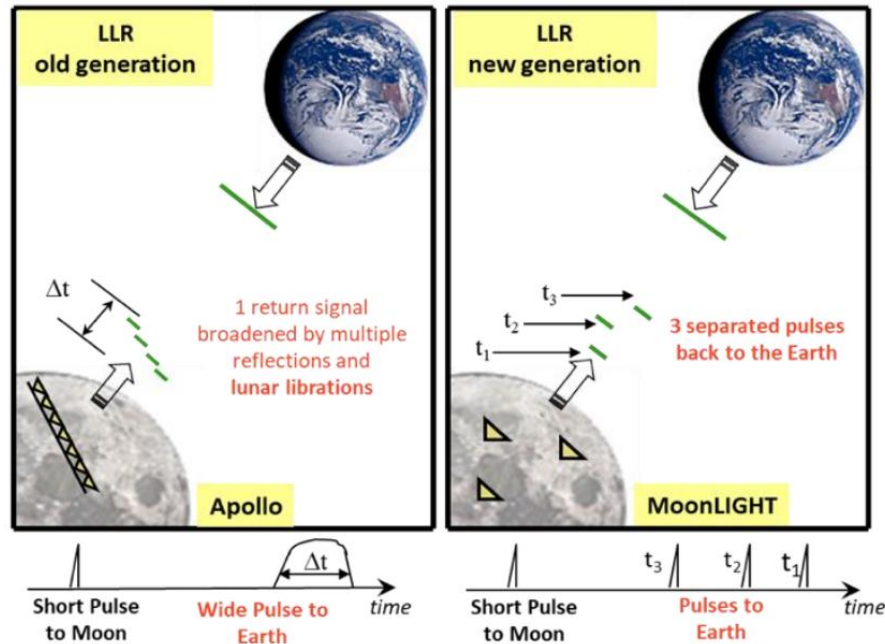


Fig.5. Comparison between the broadening of the laser return pulse from old generation LRAs due to the libration tilt (left) vs separated laser return pulses from next-gen CCRs unaffected by lunar librations (right).

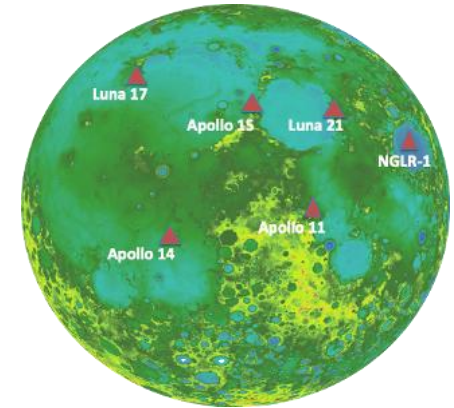


Fig. 6. Modern location of retroreflectors on the Moon's surface.

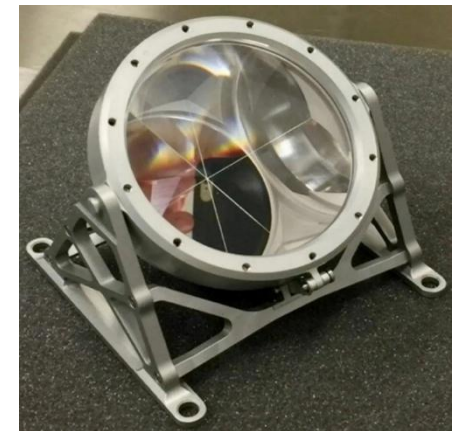


Fig.7. Monolithic NGLR reflector.

	X, m	Y, m	Z, m
ILRS	776764.3	1448332.0	552142.0
LRO	776670.46	1448357.18	552192.02
INPOP21a	776672.73 ± 0.02	1448360.19 ± 0.08	552206.52 ± 0.09
DE440	776673.16 ± 0.01	1448359.92 ± 0.11	552206.71 ± 0.08
EPM	776673.05 ± 0.01	1448359.01 ± 0.07	552204.89 ± 0.08
EPM (general solution)	776673.05 ± 0.04	1448359.11 ± 0.11	552204.96 ± 0.09

Table 2. Coordinates obtained using various ephemerides [25, 26, 32]

	X, m	Y, m	Z, m
LRO	-93,84	25,18	50,02
INPOP21a	-91.57	28.19	64.52
DE440	-91.14	27.92	64.71
EPM	-91.25	27.01	62.89
EPM (general solution)	-91.25	27.11	62.96

Table 3. Differences between the calculated NGLR-1 coordinates and the coordinates published by ILRS.

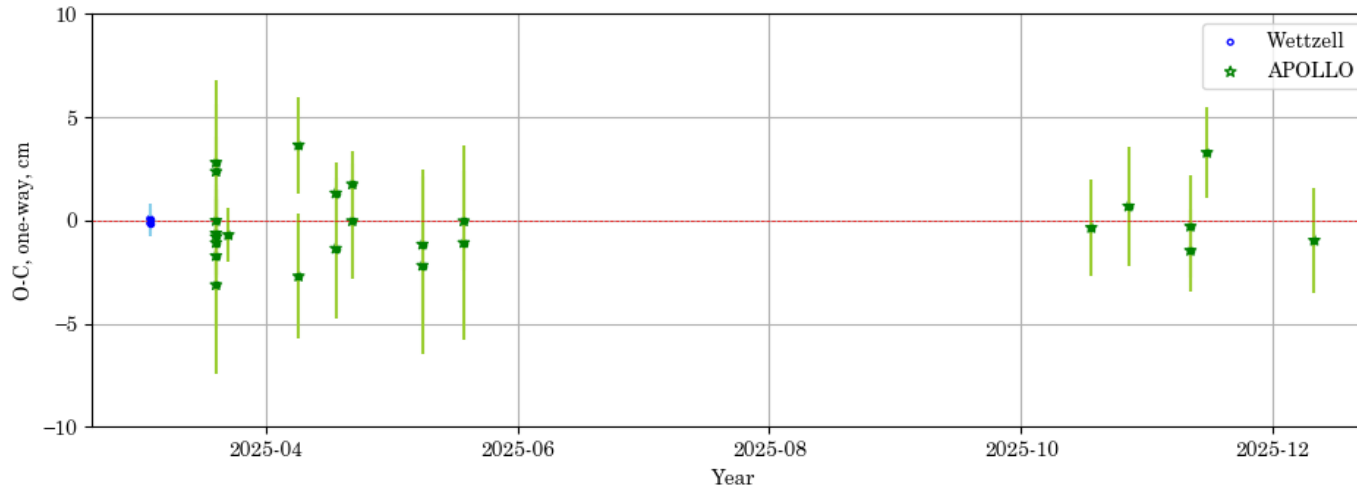


Fig. 8. Residual O-C discrepancies for observations of the NGLR-1 retroreflector at the Wettzell and APOLLO stations between April and December 2025.

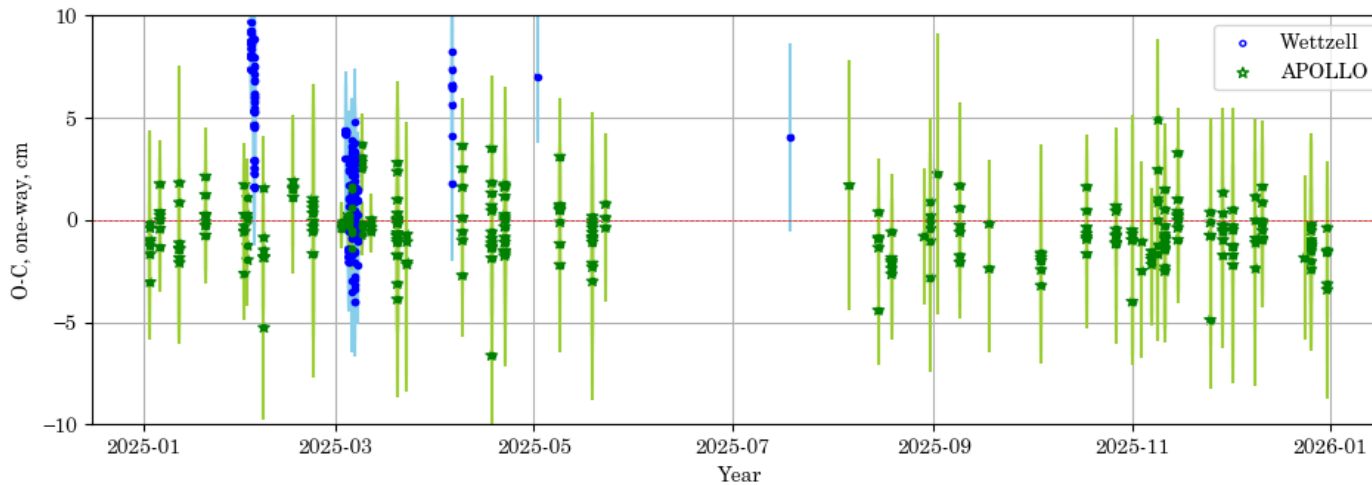


Fig. 9. Residual O-C discrepancies for observations of old retroreflectors at the Wettzell and APOLLO stations between April and December 2025.

In EPM, station coordinates are primarily used as fixed calculated values. However, they can also be represented as a linear trend.

The rates of change in the coordinates of most LLR stations have been calculated.

Station	l rate, mas/yr	px rate, mm/yr	py rate, mm/yr
Apache	-0.494 ± 0.004	4.112 ± 0.098	-2.583 ± 0.209
Haleakala	-1.877 ± 0.069	-26.407 ± 1.474	10.622 ± 3.370
McDonald	-0.443 ± 0.017	5.060 ± 0.251	2.465 ± 0.597
CERGA	0.916 ± 0.002	-11.525 ± 0.062	13.980 ± 0.110
Matera	0.853 ± 0.088	-14.048 ± 1.112	23.501 ± 3.068

Table 5. rates of change in the coordinates of LLR stations.

Station	RMS before	RMS after
Apache	0.0291	0.0285
Haleakala	0.104	0.100
McDonald	0.429	0.425
CERGA	0.336	0.335
Matera	0.0653	0.0645

Table 6. Old and new RMS of LLR stations.

The coordinate discrepancies of these stations decreased by 1-10%. The total RMS of the lunar ephemeris also decreased by 0.01.

The next version of the EPM ephemeris, EPM2026, is planned to be released this year. It will be based on next improvements:

- NGLR-1 coordinates.
- New observations.
- Re-processed observations of planets and satellites made at the Pulkovo Observatory [27].
- New reference Julian date (2453371.5).
- The rates of change in the coordinates of LLR stations.

Reasons for the modernization of the ERA system:

- From 2021, Racket does not support 80-bit variables (extflonum) [28, 29].
- Improving programming convenience – switching to more popular programming languages.
- Increasing the speed of program execution (Now the average integration time is about 12 hours for one of the iterations.)

Choice of programming language for modernizing of ERA system

Criteria:

- Ability to work with 80-bit variables (or higher)
- Speed of calculation (including possibility of parallel programming)
- Popularity

Candidates:

- Racket (bigfloat)
- C++ (MPFR / QD)
- Python (gmpy / mpmath)
- Fortran

language	64-bit	80-bit	128-bit	160-bit	256-bit
C++ --o0	0.065	0.095	0.70*/0.15**	0.68*	0.79*/1.23**
Fortran --o0	0.011	0.029	0.12		
C++ --o2	0.009	0.022	0.47*/0.024**	0.46*	0.54*/0.20**
Fortran --o1	0.009	0.022	0.11		
Racket	0.022	0.053	6.71*	6.61*	6.94*
Python	0.26	0.64*/3.68***	0.63*/2.95***	0.65*/2.97***	0.73*/2.96***

Table 6. Duration of arithmetic multiplication operations (in seconds).

language	64-bit	80-bit	128-bit	160-bit	256-bit
C++ --o0	0.75	0.89	3.40*/0.88**	3.44*	3.60*/0.99**
Fortran --o0	4.50	4.57	4.64		
C++ --o2	0.72	0.84	2.52*/0.81**	2.55*	2.69*/--**
Fortran --o2	4.48	4.52	4.60		
Racket	14.8	15.2	21.9*	21.9*	22.6*
Python	2.40	4.29*/19.6***	4.46*/19.6***	4.38*/19.6***	4.56*/19.8***

Table 7. Duration of reading from the text file (in seconds).

language	64-bit	80-bit	128-bit	160-bit	256-bit
C++ --o0	3.45	3.93	14.9*/4.18**	15.3*	16.6*/4.52**
C++ --o2	3.41	3.86	13.8*/4.17**	14.1*	15.2*/4.51**
Racket	55.8	56.1	83.9*	85.1*	89.4*
Python	7.47	21.6*/22.1***	21.8*/24.9***	22.2*/26.1***	23.6*/29.7***

Table 8. Duration of the record in the database (in seconds).

Conclusion: the most rational approach to modernizing ERA would be to use the C/C++ and Fortran languages [30].

Currently, work has begun on porting the main computing modules of the ERA system to the C/C++ programming language. As well as maintaining the required accuracy of ephemeris calculations, the use of this language will significantly reduce computation time and lay the groundwork for improving their accuracy.

Conclusion



By the end of 2026, a new version of the EPM ephemeris, EPM2026, will be prepared for release based on an updated database of optical and lunar laser ranging observations of Solar System bodies, as well as an expanded set of dynamic model parameters.

For the planned ERA system update, the C/C++ programming language has been selected, and a plan has been outlined to automate the conversion of the system's main computing modules from Racket to C/C++.

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Thank you very much for your attention !