Solar System Simulator – Technical Notes

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Introduction

The Solar System Simulator is written in Java. Positions and velocities of planets, moons, small solar system bodies and spacecraft are continuously updated using either Newton Mechanics or General Relativity. Initial positions and velocities are obtained from Nasa JPL's ephemerides. While simulating, both simulated positions and ephemeris data are visualised for comparison. Source code is made publicly availaible under the MIT licence.

Simulation

Position and velocity of each particle is updated each time step using a Runge-Kutta scheme (General Relativity, time step 1 hour) or Adams-Bashforth-Moulton scheme (Newton Mechanics, time step 0.5 hour). Computing acceleration requires interaction between all pairs of particles, and therefore, the simulation is computationally expensive. To save computation time, smaller bodies such as comets and spacecraft do not apply forces to other particles. General Relativity may be applied to obtain even more accurate simulation results. It should be noted that General Relativity requires much more computational effort compared to Newton Mechanics.

In case you want to run longer lasting simulations (say more than a century), it is possible to run the simulation without a graphical user interface and store intermediate results. See `CreateSolarSystemStateFiles.java` for example code. The files can be loaded into the simulator for visual inspection and/or continuation of the simulation.

Both the Runge-Kutta scheme and the Adams-Bashforth-Moulton scheme allow advancing with a negative timestep. Thus, it is also possible to simulate backward in time.

Ephemerides

Initial positions and velocities of the Solar System bodies are needed to run a simulation. In the simulator, ephemeris data is continuously computed such that simulation data (blue orbit lines) and ephemeris data (green orbit lines) can be compared at all times. Ephemerides data is computed such that the ecliptic plane corresponds to the x-y plane. In the Earth-to-Sun viewing mode, the ecliptic would be horizontal, whereas in reality the ecliptic plane would be tilted due to the fact that the Earth's axis is tilted. This should be noted when comparing a simulated Venus transit with drawings or pictures taken during the event.

Ephemerides for Sun, Moon, and major planets (including Pluto)

For dates between January 1, 1600 and January 31, 2200, DE405 is used. For other dates between 3000 BC and AD 3000, an approximate ephemeris is used. Ephemerides data for the Moon before January 1, 1620 or after January 31, 2200 is approximated using DE405 ephemeris data (see `EphemerisSolarSystem.java` for the code).

Ephemerides for Galilean Moons
Computation of ephemerides for the Galilean Moons is based on FORTRAN source code that has been made publicly avaiable by IMCCE Observatoire de Paris (see `EphemerisGalileanMoons.java`). To obtain accurate simulation results, the Galilean Moons are simulated using a separate particle system consisting of Jupiter and the four moons, with Jupiter remaining at the origin (see `JupiterSystem.java` and `SolarSystem.java`). Computation of ephemerides and simulation of the moons of Saturn, Uranus, and Neptune are done in a similar fashion.

Ephemerides for remaining Solar System bodies
Ephemeris data for the remaining bodies is computed from orbital parameters obtained from the JPL Small-Body Database browser and HORIZONS.

Example event in the Solar System
On September 1, 2017, Asteroid 3122 Florence passed the Earth at a distance of about 7066000 km. In Table 1, ephemeris data is compared to simulation results obtained with Newton Mechanics and General Relativity. Simulation was started at April 1, 2017 with time steps of 1 minute and 1 hour, respectively. See `FlorenceEarthExperiment.java` for the code. It can be observed that simulation data deviates from the ephemeris data. This is due to the gravitational pull of the Earth-Moon system on Florence.

Method	Timestep	Min Distance	Date/time
Ephemeris	1 minute	7066675.82 km	2017-09-01 12:07
Ephemeris	1 hour	7066677.97 km	2017-09-01 12:00
Newton Mechanics	1 minute	7053326.36 km	2017-09-01 11:55
Newton Mechanics	1 hour	7053327.45 km	2017-09-01 12:00
General Relativity	1 minute	7053314.46 km	2017-09-01 11:55
General Relativity	1 hour	7053315.56 km	2017-09-01 12:00

Table 1: Minimum distance between Earth and Florence, and time at which distance was minimal for ephemeris data and various methods of simulation.

Simulation accuracy
To obtain some insight in the accuracy of the simulation results, the major planets, the Sun, the Moon, and Pluto were simulated for 580 years. The simulation was started at January 1, 1620. During the simulation, the deviation in position compared to the DE405 Ephemeris was calculated each day. Average deviation was calculated each year. As may be expected, the deviation steadily increased over the years. In Table 2, the average deviation for each body is shown for the 100th simulated year and in Table 3, the average deviation for each body is shown for the 580th simulated year. It can be observed that using General Relativity leads to more accurate results for the inner planets, whereas for the outer planets the difference is relatively small. The results shown in Tables 2 and 3 were obtained by running `SimulationAccuracyExperiment.java`.

Solar System body	Newton Mechanics	General Relativity
Mercury	18625 km	8 km
Venus	8766 km	1 km
Earth	5876 km	22 km
Moon	5972 km	1783 km
Mars	4310 km	28 km
Jupiter	323 km	179 km
Saturn	211 km	2 km
Uranus	130 km	60 km
Neptune	130 km	91 km
Pluto	77 km	91 km

Table 2: Deviation in position after 100 years of simulation.

Solar System body	Newton Mechanics	General Relativity
Mercury	109733 km	124 km
Venus	51135 km	2 km
Earth	34227 km	104 km
Moon	34833 km	8249 km
Mars	24951 km	472 km
Jupiter	2227 km	1120 km
Saturn	1301 km	26 km
Uranus	867 km	431 km
Neptune	541 km	344 km
Pluto	172 km	237 km

Table 3: Deviation in position after 580 years of simulation.

Oblate spheroids

The Earth and other planets are not real spheres, rather they are somewhat flattened. This flattening has influence on the acceleration applied to bodies near by such as moons and artificial satellites. In Tables 4 and 5, results are shown of similar simulations as in Tables 2 and 3, except that the acceleration of the Moon due to Earth's gravity is computed by representing the Earth as an oblate spheroid.

Solar System body	Newton Mechanics	General Relativity
Mercury	18626 km	8 km
Venus	8766 km	1 km
Earth	5822 km	50 km
Moon	5825 km	55 km
Mars	4310 km	28 km
Jupiter	323 km	179 km
Saturn	211 km	2 km
Uranus	130 km	60 km
Neptune	130 km	91 km
Pluto	77 km	91 km

Table 4: Deviation in position after 100 years of simulation with oblate Earth.

Solar System body	Newton Mechanics	General Relativity
Mercury	109734 km	124 km
Venus	51136 km	3 km
Earth	33906 km	294 km
Moon	33891 km	1900 km
Mars	24950 km	473 km
Jupiter	2227 km	1120 km
Saturn	1301 km	26 km
Uranus	867 km	431 km
Neptune	541 km	343 km
Pluto	172 km	237 km

Table 5: Deviation in position after 580 years of simulation with oblate Earth.

Table 6 shows the effect of oblateness of the Earth, Jupiter, Saturn, Uranus, and Neptune on the deviation in position of all moons after 2 years of simulation (Jan 1, 1985 – Jan 1, 1987). Deviations are averaged during the second year of simulation. Deviation in position of the planet is with respect to the Sun. Deviation in position of the moons is with respect to their planet. With the exception of Ariel, deviation is considerably reduced due to oblateness. The effect of applying General Relativity (GR) is relatively small. The results in Table 6 were obtained by running `SolarSystemMoonsExperiment.java`.

Planet/Moon	NM No oblateness	NM Oblateness	GR Oblateness
Earth	88.7 km	89.0 km	0.6 km
- Moon	27.3 km	4.7 km	1.2 km
Jupiter	1.9 km	1.9 km	0.2 km
- Io	587936 km	266 km	309 km
- Europa	176881 km	273 km	297 km
- Ganymede	117158 km	356 km	371 km
- Callisto	137554 km	240 km	229 km
Saturn	0.5 km	0.5 km	0.3 km
- Mimas	236350 km	13856 km	13840 km
- Enceladus	241497 km	4131 km	4119 km
- Tethys	559919 km	8363 km	8352 km
- Dione	338262 km	4909 km	4898 km
- Rhea	50130 km	7752 km	7745 km
- Titan	106383 km	3667 km	3663 km
- Iapetus	73241 km	1817 km	1815 km
Uranus	0.4 km	0.4 km	0.3 km
- Miranda	63131 km	1053 km	1056 km
- Ariel	4163 km	8735 km	8738 km
- Umbriel	31487 km	7383 km	7381 km
- Titania	32521 km	3250 km	3249 km
- Oberon	30121 km	2351 km	2350 km
Neptune	0.3 km	0.3 km	0.3 km
- Triton	77912 km	4.9 km	29 km

Table 6: Effect of oblateness on deviation in position of moons.

Spacecraft
In Tables 7 through 11, the expected and actual date/times and distances during flyby's of Pioneer 10, Pioneer 11, Voyager 1, Voyager 2, and New Horizons are shown. Results were obtained by running `SpacecraftExperiment.java`. Results are shown for Newton Mechanics with time step of 1 minute. Similar results were obtained using General Relativity with a time step of 1 minute (not shown).

Pioneer 10

Flyby	Date/time expected	Date/time actual	Distance expected	Distance actual
Callisto	1973-12-03 12:26	1973-12-03 09:54	1,392,300 km	1,409,298 km
Ganymede	1973-12-03 13:56	1973-12-03 14:05	446,250 km	448,280 km
Europa	1973-12-03 19:26	1973-12-03 19:39	321,000 km	319,167 km
Io	1973-12-03 22:56	1973-12-03 23:02	357,000 km	356,522 km
Jupiter	1973-12-04 02:26	1973-12-04 02:21	200,000 km	202,359 km

Table 7: Expected and actual results for flyby's Pioneer 10.
Expected date/time and distance obtained from
https://en.wikipedia.org/wiki/Pioneer_10

Pioneer 11

Flyby	Date/time expected	Date/time actual	Distance expected	Distance actual
Callisto	1974-12-02 08:21	1974-12-02 08:17	786,500 km	781,211 km
Ganymede	1974-12-02 22:09	1974-12-02 22:11	692,300 km	690,444 km
Io	1974-12-03 03:11	1974-12-03 13:08	314,000 km	313,383 km
Europa	1974-12-03 04:15	1974-12-03 04:19	586,700 km	586,710 km
Jupiter	1974-12-03 05:21	1974-12-03 05:22	42,428 km from surface	42,647 km from surface
Iapetus	1979-08-29 06:06	1979-08-29 06:11	1,032,535 km	1,033,134 km
Dione	1979-09-01 16:00	1979-09-01 16:05	291,556 km	291,850 km
Mimas	1979-09-01 16:26	1979-09-01 16:33	104,263 km	104,339 km
Saturn	1979-09-01 16:30	1979-09-01 16:34	20,591 km from surface	20,481 from surface
Tethys	1979-09-01 18:26	1979-09-01 18:27	329,197 km	332,130 km

Enceladus	1979-09-01 18:30	1979-09-01 18:33	222,027 km	225,919 km
Rhea	1979-09-01 22:15	1979-09-01 22:46	345,303 km	339,040 km
Titan	1979-09-02 18:01	1979-09-02 18:03	362,962 km	344,837 km

Table 8: Expected and actual results for flyby's Pioneer 11.
Expected date/time and distance obtained from
https://en.wikipedia.org/wiki/Pioneer_11

Voyager 1

Flyby	Date/time expected	Date/time actual	Distance expected	Distance actual
Jupiter	1979-03-05 12:05:26	1979-03-05 12:06	348,890 km	348,307 km
Io	1979-03-05 15:14	1979-03-05 15:15	20,570 km	20,520 km
Europa	1979-03-05 18:19	1979-03-05 17:20	733,760 km	732,975 km
Ganymede	1979-03-06 02:15	1979-03-06 02:17	114,710 km	113,168 km
Callisto	1979-03-06 17:08	1979-03-06 17:10	126,400 km	124,106 km
Titan	1980-11-12 05:41:21	1980-11-12 05:40	6,490 km	4,684 km
Tethys	1980-11-12 22:16:32	1980-11-12 22:15	415,670 km	422,178 km
Saturn	1980-11-12 23:46:30	1980-11-12 23:44	184,300 km	190,511 km
Mimas	1980-11-13 01:43:12	1980-11-13 01:39	88,440 km	94,888 km
Enceladus	1980-11-13 01:51:16	1980-11-13 01:48	202,040 km	212,923 km
Rhea	1980-11-13 06:21:53	1980-11-13 06:24	73,980 km	56,154 km

Table 9: Expected and actual results for flyby's Voyager 1.
Expected date/time and distance obtained from
https://en.wikipedia.org/wiki/Voyager_1

Voyager 2

Flyby	Date/time expected	Date/time actual	Distance expected	Distance actual
Callisto	1979-07-08 12:21	1979-07-08 12:22	214,930 km	215,539 km
Ganymede	1979-07-09 07:14	1979-07-09 07:15	62,130 km	61,407 km
Europa	1979-07-09 17:53	1979-07-09 17:51	205,720 km	205,539 km

Jupiter	1979-07-09 22:29	1979-07-09 22:29	721,670 km	721,772 km
Io	1979-07-09 23:17	1979-07-09 23:18	1,129,900 km	1,129,812 km
Iapetus	1981-08-22 01:26:57	1981-08-23 01:27	908,680 km	908,846 km
Titan	1981-08-25 09:37:46	1981-08-25 09:37	666,190 km	663,766 km
Dione	1981-08-26 01:04:32	1981-08-26 01:03	502,310 km	500,624 km
Mimas	1981-08-26 02:24:26	1981-08-26 02:33	309,930 km	308,951 km
Saturn	1981-08-26 03:24:05	1981-08-26 03:23	161,000 km	159,077 km
Enceladus	1981-08-26 03:45:16	1981-08-26 03:41	87,010 km	89,518 km
Tethys	1981-08-26 06:12:30	1981-08-26 06:09	93,010 km	94,050 km
Rhea	1981-08-26 06:28:48	1981-08-26 06:30	645,260 km	641,566 km
Miranda	1986-01-24 16:50	1986-01-24 17:01	29,000 km	31,934 km
Ariel	1986-01-24 17:25	1986-01-24 16:19	127,000 km	129,779 km
Umbriel	1986-01-24 17:25	1986-01-24 20:51	325,000 km	316,195 km
Titania	1986-01-24 17:25	1986-01-24 15:08	365,200 km	368,394 km
Oberon	1986-01-24 17:25	1986-01-24 16:09	470,600 km	473,595 km
Uranus	1986-01-24 17:59:47	1986-01-24 17:56	107,000 km	101,306 km
Neptune	1989-08-25 03:56:36	1989-08-25 03:56	4,950 km from surface	4,689 km from surface
Triton	1989-08-25 09:23	1989-08-25 09:11	39,800 km	39,754 km

Table 10: expected and actual results for flyby's Voyager 2. Expected date/time and distance obtained from https://en.wikipedia.org/wiki/Voyager_2

New Horizons

Fly by	Date/time expected	Date/time actual	Distance expected	Distance actual
Jupiter	2007-02-28 05:43:40	2007-02-28 05:49	2.3 million km	2,302,925 km
Pluto	2015-07-14 11:49	2015-07-14 11:37	13,658 km	13,256 km
Ultima Thule	2019-01-01 05:33	2019-01-01 05:35	3,500 km	3,561 km

Table 11: Expected and actual results for flyby's New Horizons
Expected date/time and distance obtained from
https://en.wikipedia.org/wiki/New_Horizons

In Figure 1, the simulated velocity of Voyager 2 is plotted against the distance from the Sun. It can be observed that the velocity increases due gravity assist each time the spacecraft passes a planet. These results were obtained by running `SpacecraftVelocityDistanceExperiment.java`.

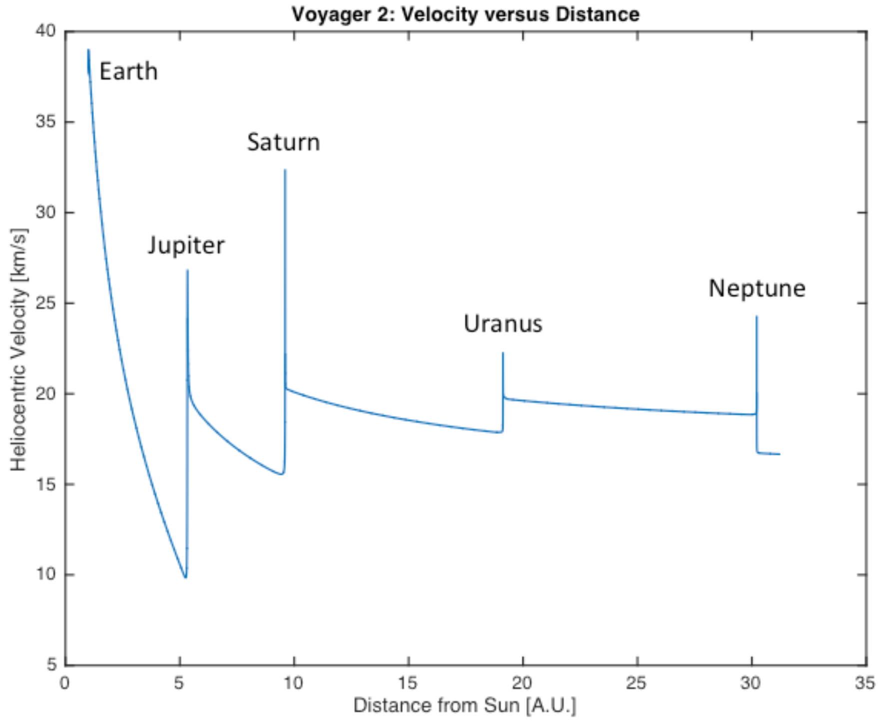

Figure 1: Velocity versus distance for Voyager 2.

Halley's Comet

In Table 10, expected and simulated perihelion passages of Halley's Comet are shown. Simulation was started February 17, 1994 and ran backward with time step 1 hour. Results are shown for Newton Mechanics. Similar results were obtained for General Relativity. These results were obtained by running `HalleyPerihelionPassageExperiment.java`.

Observed	Simulated	Difference
BC 240-05-15	BC 240-07-29	75 days
BC 164-05-20	BC 163-01-21	244 days
BC 87-08-15	BC 87-08-18	3 days
BC 12-10-08	BC 12-10-12	4 days
AD 66-01-26	AD 66-01-10	15 days
AD 141-03-25	AD 141-02-26	26 days
AD 218-04-06	AD 218-04-12	6 days
AD 295-04-07	AD 295-03-30	7 days
AD 374-02-13	AD 374-01-11	32 days

AD 451-07-03	AD 451-06-03	29 days
AD 530-11-15	AD 530-09-22	53 days
AD 607-03-26	AD 607-03-29	3 days
AD 684-11-26	AD 684-10-19	37 days
AD 760-06-10	AD 760-05-17	23 days
AD 837-02-25	AD 837-01-29	26 days
AD 912-07-27	AD 912-07-15	11 days
AD 989-09-02	AD 989-09-28	26 days
AD 1066-03-25	AD 1066-04-15	21 days
AD 1145-04-19	AD 1145-05-17	28 days
AD 1222-09-10	AD 1222-10-09	29 days
AD 1301-10-22	AD 1301-10-09	12 days
AD 1378-11-09	AD 1378-10-14	25 days
AD 1456-01-08	AD 1456-05-17	130 days
AD 1531-08-26	AD 1531-08-06	19 days
AD 1607-10-27	AD 1607-10-13	13 days
AD 1682-09-15	AD 1682-09-12	2 days
AD 1758-03-13	AD 1759-03-06	358 days[1]
AD 1835-11-16	AD 1835-11-08	7 days
AD 1910-04-20	AD 1910-04-16	3 days
AD 1986-02-09	AD 1986-02-09	0 days

Table 12: Expected and simulated perihelion passages of Halley's Comet. Expected perihelion passages obtained from https://en.wikipedia.org/wiki/Halley%27s_Comet

[1]The difference between the simulated and expected perihelion passage in 1758 is almost one year. The expected year should be 1759 instead of 1758 (See https://ssd.jpl.nasa.gov/sbdb.cgi?sstr=1P) reducing the difference to 6 days.

Precession of the perihelion of Mercury

The orbit of Mercury is not only affected by the gravitational forces of the other planets, but also by the fact that spacetime is disturbed by the Sun's mass. This leads to the precession of the perihelion of Mercury. In the Solar System Simulator, this effect can be observed when simulating with General Relativity and comparing the results to a simulation with Newton Mechanics.

Two experiments have been defined to investigate the precession of the perihelion of Mercury. In one experiment, a two-particle system with the Sun and Mercury is simulated with Newton Mechanics and General Relativity for one hundred, one thousand, and ten thousand years (`MercuryPrecessionTwoParticleExperiment.java`). In another experiment, the entire Solar System is simulated for one hundred and one thousand years (`MercuryPrecessionSolarSystemExperiment.java`).

Perihelion precessions measured in the experiments are listed in Table 11. Observed precession of the perihelion of Mercury is 574.10±0.65 arcsec/Julian century. Of the observed precession, 532.30 arcsec/century can be explained by gravitational pull of other bodies. For more information, see https://en.wikipedia.org/wiki/Tests_of_general_relativity.

Experiment	Duration	Newton Mechanics	General Relativity	Difference
Two particles	100 years	0.1244	42.8942	42.7698
Two particles	1000 years	0.0088	42.9873	42.9785
Two particles	10000 years	0.0024	42.9830	42.9806
Solar system	100 years	527.47	570.38	42.92
Solar system	1000 years	533.65	576.49	42.84

Table 13: Precession of the perihelion of Mercury.

Java code

To get an overview of the code you can generate JavaDoc. Unittests are provided for the supporting classes EphemerisUtil, JulianDataConverter, and Vector3D. In addition, a unittest is provided for the EphemerisAccurate class to check for consistency over the entire period of 580 years for which this ephmeris is valid.

Acknowledgements

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References

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https://en.wikiversity.org/wiki/Adams-Bashforth_and_Adams-Moulton_methods

Runge-Kutta numerical scheme:
http://physics.bu.edu/py502/lectures3/cmotion.pdf

Update scheme for General Relativity (see equation 27 on page 12):
https://ipnpr.jpl.nasa.gov/progress_report/42-196/196C.pdf

3122 Florence
https://en.wikipedia.org/wiki/3122_Florence

Approximate Ephemeris
https://ssd.jpl.nasa.gov/txt/aprx_pos_planets.pdf

JPL Planetary and Lunar Ephemerides
https://ssd.jpl.nasa.gov/?planet_eph_export

JPL Small-Body Database Browser
https://ssd.jpl.nasa.gov

HORIZONS Web-Interface
https://ssd.jpl.nasa.gov/horizons.cgi

DE405 ephemeris files
ftp://ssd.jpl.nasa.gov/pub/eph/planets/ascii/de405/

Source code DECheck.java on which EphemerisAccurate.java is based.
ftp://ssd.jpl.nasa.gov/pub/eph/planets/JAVA-version/java.src

Fortran source code ephemeris for Galilean Moons
ftp://ftp.imcce.fr/pub/ephem/satel/galilean/L1/L1.1/