Solar System Simulator – Technical Notes

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Introduction

The Solar System Simulator is written in Java. Positions and velocities of 30 solar system bodies and 3 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. Computing acceleration requires interaction between all pairs of particles, and therefore, the simulation is computationally expensive. Although Newton Mechanics with a time step of 1 hour suffices in most cases, a smaller time step and/or General Relativity may be applied to obtain even more accurate simulation results, especially when bodies are moving fast (e.g. Mercury). 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.

The Runge-Kutta scheme allows 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, 1620 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`).

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	7053326.41 km	2017-09-01 11:55
Newton Mechanics	1 hour	7053327.51 km	2017-09-01 12:00
General Relativity	1 minute	7053314.52 km	2017-09-01 11:55
General Relativity	1 hour	7053315.61 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	18651 km	8 km
Venus	8766 km	1 km
Earth	5876 km	22 km
Moon	5955 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	110576 km	124 km
Venus	51136 km	2 km
Earth	34226 km	104 km
Moon	34325 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.

Spacecraft

In Tables 4 through 6, the expected and actual date/times and distances during flyby's of 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 when using General Relativity with time step of 1 minute.

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	20,471 km
Europa	1979-03-05 18:19	1979-03-05 17:21	733,760 km	729,949 km
Ganymede	1979-03-06 02:15	1979-03-06 02:15	114,710 km	124,825 km
Callisto	1979-03-06 17:08	1979-03-06 17:10	126,400 km	123,872 km
Titan	1980-11-12 05:41	1980-11-12 05:41	6,490 km	6,493 km
Saturn	1980-11-12	1980-11-12	184,300 km	190,511 km

	23:46:30	23:44		

Table 4: 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	215,038 km
Ganymede	1979-07-09 07:14	1979-07-09 07:19	62,130 km	53,918 km
Europa	1979-07-09 17:53	1979-07-09 17:52	205,720 km	207,575 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 23:17	1,129,900 km	1,129,427 km
Titan	1981-08-25 09:37	1981-08-25 09:49	666,190 km	679,868 km
Saturn	1981-08-26 03:24:05	1981-08-26 03:23	161,000 km	159,076 km
Uranus	1986-01-24 17:59:47	1986-01-24 17:57	107,000 km	102,340 km
Neptune	1989-08-25 03:56:36	1989-08-25 04:04	4,950 km	35,359 km

Table 5: 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	14,391 km
Ultima Thule	2019-01-01 05:33	2019-01-01 06:44	3,500 km	26,752 km

Table 6: Expected and actual results for fly by'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`.

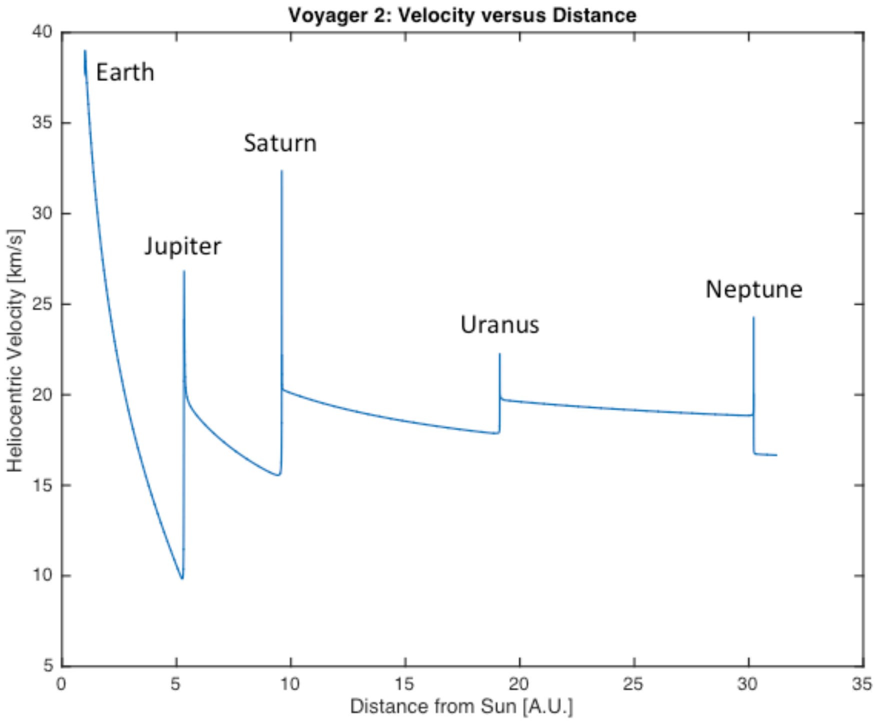

Figure 1: Velocity versus distance for Voyager 2.

Halley's Comet
In Table 7, 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 7: 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 8. 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 8: 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

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/