

Orbital Mechanics Simulations by Means of Numerical Methods

HÅKON TANSEM, NILS-OLE STUTZER, AND BERNHARD NORNES LOTSBERG

Abstract

1. INTRODUCTION

Celestial mechanics is a physical problem that has intreeged mankind since the day of time. It has fascinated astronomers since night time observations done by the antient greeks, through Galileo Galilei's studies of Jupiters moons in the Renaissance, to todays detailed observations and simulations. At the present date one can do detailed numerical simulations of the motion of planets and other celestial objects, so as to predict their motion many centuries into the future.

In this paper we will study how the celestial bodies in our Solar System interact using two different numerical methods for solving the coupled differential equations of motion discribing their movement. We will look at the classical Forward Euler and the more advanced Velocity Verlet methods, and compare them. In addition we will study different versions of the gravitational force to see how it affects the planets orbit, and also we will see what happens to the Earth's and Sun's motion if Jupiters mass is changes. Last we will study Mercury's perihelion precession.

We will present theory and its implementation in the Method section. The results of our study will be presented and discussed in the Results and Discussion section respectively.

2. METHOD

2.1. The Gravitational force and the Equations of Motion

The motion of celestial bodies in the solar system are governed by one single force, being the gravitational force. In Newtonian physics this is written as

$$\vec{F} = -G \frac{Mm}{r^3} \vec{r}, \quad (1)$$

where F is the force between two masses M and m separated by a distance \vec{r} ($r = |\vec{r}|$) and G is the gravitational constant. More generally when having more than just two celestial bodies (N bodies), the force on one of them m_i is simply the sum of the gravitational force from all the other bodies m_j . Thus we have the total gravita-

tional force

$$\vec{F}_i = \sum_i^N \sum_{j \neq i}^N -G \frac{m_i m_j}{|\vec{r}_j - \vec{r}_i|^3} (\vec{r}_j - \vec{r}_i) = m_i \vec{a}_i = m_i \ddot{\vec{r}}_i, \quad (2)$$

where we used Newton's second law to find the acceleration. In this N -body problem celestial bodies are interacting with each other, affecting each others motions. When simulating our Solar System, it is often common to let the Sun be static at the origin due to its mass being many orders of magnitude larger than that of the planet, limiting its motion to a small wiggle. We will however include the Suns motion in our simulations, as it reflects reality better than having it static.

When simulating the motions of the celestial bodies according to the force (2) it is convenient to chose a scaling more suited to the scales of the Solar System. To find such a scaling we consider the gravitational force between Earth and the Sun in a circular orbit. We then get

$$F = G \frac{M_{\oplus} M_{\odot}}{r^2} = \frac{v^2}{r} M_{\oplus}, \quad (3)$$

using that gravity equals the centripetal force in a circular orbit. Since we know that for a circular orbit $v = \frac{2\pi r}{T}$, for an orbital periode $T = 1\text{yr}$, we get that the gravitational constant becomes

$$G = 4\pi^2 \frac{\text{AU}^3}{\text{yr}^2 M_{\odot}}, \quad (4)$$

since the relative Sun-Earth distance in a circular orbit is 1AU. Thus we use units solar masses M_{\odot} , astronomical units AU for distances and years yr for time, as they are far easier to handle.

In order to solve the equations of motion we can write the second order ordinary differentail equation (ODE) as a system of two coupled first order equations. Further more as the equations are vector equations, we can write the coupled system of equations for body i component wise as

$$v_x^i = \frac{dx^i}{dt} = \dot{x}^i \text{ and } a_x^i = \frac{dv_x^i}{dt} = \ddot{x}^i, \quad (5)$$

and similarly for the y and z components. Thus when simulation N bodies in three dimensions we would need $6N$ coupled differential equations.

2.2. Discretization and Numerical Solvers

When solving the system of $6N$ coupled ODEs numerically we need to discretize the equations. We do this by letting $x(t) \rightarrow x(t_i) = x_i$ where the time $t \rightarrow t_i = a + ih$, with $t \in [a, b]$ and $i = 0, 1, 2, \dots, n-1$. Then $a \rightarrow t_0$, $b \rightarrow t_n$ and the time step $h = \frac{b-a}{n}$ for n time steps. Using this discretization the position in the next time step is written as $x(t_i + h) = x_{i+1}$.

From the Taylor expansion

$$x_{i+1} = x_i + h\dot{x}_i + \frac{h^2}{2}\ddot{x}_i + \mathcal{O}(h^3) \quad (6)$$

we can get Eulers Forward algorithm when only keeping first order terms. This then becomes

$$x_{i+1} = x_i + hv_x^i + \mathcal{O}(h^2), \quad (7)$$

inserting that $v_x^i = \dot{x}_i$. Similarly, the second coupled ODE can be written

$$v_x^{i+1} = v_x^i + h\dot{v}_x^i = v_x^i + ha_x^i + \mathcal{O}(h^2). \quad (8)$$

This algorithm is very simple and requires only a few floating point operations (FLOPs) per time step, however, the trade-off is that it is quite inaccurate having an error term $\mathcal{O}(h^2)$.

Another numerical method more commonly used is the Velocity Verlet algorithm. It has the advantage of being more accurate than the Forward Euler, having a mathematical error term of $\mathcal{O}(h^3)$, in addition to requiring about the same amount of FLOPs. Also it is tailored towards conserving the total mechanical energy and angular momentum of a Hamiltonian system such as a N -body system, because it is a symplectic integration scheme (Holmes (2007)). We can write the two coupled ODEs as

$$x_{i+1} = x_i + hv_x^i + \frac{h^2}{2}a_x^i + \mathcal{O}(h^3) \quad (9)$$

$$v_x^{i+1} = v_x^i + \frac{h}{2}[a_x^{i+1} + a_x^i] + \mathcal{O}(h^3) \quad (10)$$

Jensen (2015). As opposed to the Forward Euler we see that the two equations in this scheme are not independent of each other. To solve for the velocity at the next time step one needs the acceleration for the next time step as well. This acceleration is found through the next position x_{i+1} . These two equations thus always have to be solved together. Comparing the amount of FLOPs per time step, we find that the Forward Euler algorithm has about 4 flops per step, while the Velocity Verlet scheme has 7 if $h/2$ and $h^2/2$ are precalculated. This is remarkable, as one can construct a scheme with a superior error conserving energy and angular momentum with only a few FLOPs extra. The drawback is

of course that one has to compute an acceleration two times per step using the Velocity Verlet scheme, which was not taken into account when counting the FLOPs as the FLOPs in the acceleration are dependent on how many bodies are simulated. As both schemes have similar amounts of FLOPs we expect them to perform similarly in a timing of the algorithms.

2.3. Testing the Algorithms

To first test that the ODE solvers work properly we plot the trajectory of the Sun-Earth system with a circular orbit. This is done by letting the Earth and Sun start at a separation of 1 AU and we give them the initial velocity corresponding to a circular orbit. This is found using that the gravitational and centripetal forces are equal for a circular orbit so that

$$F = m \frac{v^2}{r} = G \frac{M_{\oplus} M_{\odot}}{r^2} \quad (11)$$

$$\Rightarrow v = \sqrt{\frac{GM_{\odot}}{r}}. \quad (12)$$

We know from classical mechanics that there are certain quantities that are constant over time, the so-called constants of motion. In our case where we consider a system of interacting in a conservative force potential, the kinetic K , potential V and total mechanical energy E as well as the angular momentum l are such constants of motion. If we consider a Sun-Earth system in the plane of the motion we get that Earth has a Lagrangian

$$L = K + V = \frac{1}{2}M_{\oplus}(\dot{r}^2 + r^2\dot{\phi}^2) + G \frac{M_{\oplus}M_{\odot}}{r}, \quad (13)$$

for an angular velocity $\dot{\phi}$. We see that since the Lagrangian L is independent of the azimuth angle ϕ we get from Lagrange's equation that

$$\frac{d}{dt} \frac{\partial L}{\partial \dot{\phi}} - \frac{\partial L}{\partial \phi} = \frac{d}{dt} \frac{\partial L}{\partial \dot{\phi}} = 0, \quad (14)$$

gives us that

$$\Rightarrow l = \frac{\partial L}{\partial \dot{\phi}} = mr^2\dot{\phi} = \text{constant}. \quad (15)$$

This is a constant of Noether's theorem, where all symmetries of a system result in a constant of motion (Leinaas (2018)), such as the invariance under an azimuth rotation in our case. Furthermore, since there are no rigid-body constraints in our system that are time-dependent the total energy of the system is given by the Hamiltonian $H = E = K + V$. If we have an explicitly time-independent Lagrangian it follows that the implicit time dependence of the Hamiltonian is given as

$$\frac{dH}{dt} = \frac{dE}{dt} = \frac{\partial L}{\partial t} = 0, \quad (16)$$

which implies that the total energy of our system must be conserved (Leinaas (2018)). In the special case of a circular orbit the kinetic and potential energies are also conserved, because the constant distance r to the center of mass (CM) gives a constant potential energy and a constant orbital speed $v = \sqrt{\frac{GM_\odot}{r}}$, i.e. a constant kinetic energy.

To check whether our numerical schemes conserve the constants of motion we simulate a Sun-Earth system over several years and plot the energies and angular momentum against time. When doing this we must correct for the motion of the CM as it is the angular momentum around the CM that is constant. The center of mass is given by the position \vec{R}_{CM} and the velocity \vec{V}_{CM} as

$$\vec{R}_{\text{CM}} = \frac{1}{M_{\text{tot}}} \sum_i^N m_i \vec{r}_i \quad (17)$$

$$\vec{V}_{\text{CM}} = \frac{1}{M_{\text{tot}}} \sum_i^N m_i \vec{v}_i \quad (18)$$

for the total mass M_{tot} .

Also to research the stability of the two algorithms over time we simulate several Sun-Earth systems using different time steps h and check how close to their starting point they get after one orbit.

2.4. Escape Velocity and Modifies Gravitational Force

Next we will consider a Sun-Earth system where the Earth starts 1 AU from the Sun. We now want to find which initial velocity the Earth must have for it to escape the Sun's gravitational field. To do this we run several simulations, each with different initial velocities. In order to determine whether the Earth has left the gravitational field of the Sun, escaping to infinity, we simply simulate the system over a large amount of time. This is, of course, not the best method since the Earth may simply orbit the Sun on a very eccentric orbit with a period longer than the simulated time. However, we will still get a rough estimate of the escape velocity when simulating over a large amount of time.

The numerical value of the escape velocity can easily be found. Consider a planet of mass m initially at escape velocity v_{esc} at radius r from the Sun. If it is to escape to infinity, where it is at rest, it will have energy $E_\infty = 0$ at $r \rightarrow \infty$. Energy conservation then gives us

$$E_0 = \frac{1}{2}mv_{\text{esc}}^2 - G\frac{M_\odot m}{r} = 0 = E_\infty, \quad (19)$$

which gives

$$v_{\text{esc}} = \sqrt{\frac{2GM}{r}}. \quad (20)$$

The planet m must thus initially have a speed of v_{esc} to escape the solar system.

Further, we want to find how the orbit of the Earth would behave like if changing the gravitational force to

$$F = -G\frac{M_\odot M_\oplus}{r^\beta}, \quad (21)$$

for some $\beta \in [2, 3]$. To do this we simulate the orbit of several different values of β and compare them. Our findings can then be theoretical expectations. According to Bertrand's theorem (Goldstein et al. 2001, ch. 3.6) the attractive central force must have a power law index $n = -\beta > -3$ for an orbit to be closed. This is so that the effective potential $U_{\text{eff}} = \frac{l^2}{2mr^2} - G\frac{M_\odot m}{(1-\beta)r^{\beta-1}}$ has a local minimum around which the planet can oscillate. This is only the case when $\beta > 3$.

2.5. The Three-Body Problem

Now that we have looked at several simpler two-body systems, it is time to consider a three-body system of the Sun, Earth and Jupiter. We will simulate the behaviour of this system for the regular masses of the involved celestial bodies, and what happens when increasing the mass of Jupiter by a factor 10 and 1000 respectively. The motion of the system as a whole was corrected by transforming into the CM frame.

We expect that the system will be quite stable when Jupiter has its regular mass, however when increasing its mass by a factor 10 we expect Jupiter's pull to affect both the Earth and Sun's motion. The Sun, even though it is very massive compared to Jupiter (about 1000 times more massive), will feel the pull of Jupiter and thus orbit the CM (which is within the Sun). Increasing the mass of Jupiter by a factor 10 will thus enlarge the orbital motion of the Sun, and the now increased pull from Jupiter may change the motion of the Earth significantly.

When increasing the mass of Jupiter by a factor 1000, we essentially simulate a double-star system, as Jupiter is now about as massive as the Sun. In this case it would be especially unrealistic to keep the Sun static, as the now added new star to the system will have a non-negligible effect on the Sun. The Sun and Jupiter should now orbit each other. The Earth may now be thrown out of the system by a sudden boost in angular momentum of one of the two more massive objects.

2.6. The Full Solar System

We have now considered a N-body simulation with two and three bodies. Next we add all planets from Mercury to Neptune, including the Sun and the dwarf planet Pluto, to our system. To see how low-mass objects behave in the Solar System simulation, we include Elon

Musk’s Tesla Roadster launched into orbit by Space-X. All initial values for the celestial bodies were kindly provided by NASA (2019). To get closed orbits for all bodies included, even Pluto, we simulate about 250 yr of time.

2.7. Mercurie’s Perihelion Precession

When looking closely at Mercury’s orbit one can see that it is not simply a static closed ellipse, but that the semi-major axis of the ellipse is rotating slowly. This is the so-called Perihelion Precession of Mercury, and is of the order of 43 arcseconds per century (Jensen, M. H. (2019)). Regular Newtonian gravity cannot account for this, however, including general relativistic effects may describe the precession better. In order to simulate this we implement the relativistic correction to Newtonian gravity written as

$$F = \frac{GM_{\odot}M_{\oplus}}{r^2} \left(1 + \frac{3l^2}{rc^2} \right), \quad (22)$$

where $l = |\vec{r} \times \vec{v}|$ is the magnitude of Mercury’s angular momentum per mass and c is the speed of light Jensen, M. H. (2019).

In order to compute the perihelion angle θ_p we use $\tan \theta_p = \frac{y_p}{x_p}$, where (x_p, y_p) is the plane position of the perihelion of Mercury. This is the point in Mercury’s orbit closest to the CM of the system. Since the perihelion precession of Mercury is so small, we need to simulate the orbits with a sufficiently small time step h and we need to simulate long enough, for instance over 100 yr. Also to avoid large amounts of saved data, we only save 0.5 yr (Earth years) of data at the beginning and end of the simulation. The difference in the angle θ_p then gives the perihelion precession. The numerically found result can then be compared to the theoretical value.

3. RESULTS

The two integration algorithms were compared testing the stability of the solutions in circular orbit. Using (likning for sirkulær bane), with $r = 1\text{AU}$ and $M = M_{\odot}$, one finds the velocity for circular orbit to be 6.28AU/Yr . Figure 1 shows the solution of the Earth-Sun system using both the Velocity-Verlet and the Forward Euler algorithm with a timestep of 1500 steps per year. Here the earth was initialized with a distance of 1AU from the sun with the calculated circular velocity. The simulation was run over two years. The same simulation was done varying the amount of steps per year and simulating over two years. This is shown in Figure 2. Here we plot the discrepancy in the distance between the initial starting point and the point after the Earth has finished

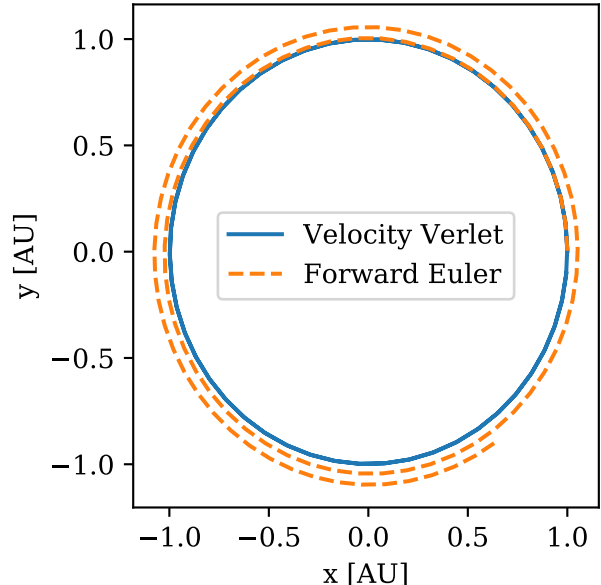


Figure 1. Trajectory Sun and Earth

one full orbit after being initialized with circular velocity as a function of timestep. The potential and kinetic energy as well as the angular momentum for the Earth was also calculated for both methods in the Earth-Sun system. The potential and kinetic energies is shown Figure 3 and the angular momentum os shown in Figure 4. The simulation was done over 200 years using 100000 steps per year. Here the earth was also initialized with a distance of 1AU from the sun with the calculated circular velocity.

When calculating the escape velocity for the Earth with respect to the Sun, we found using 20 that the escape velocity for the earth at a distance of 1AU to be 8.86AU/Yr . The Velocity-Verlet method was also tested with a varying β for the exponent in the radial term of the gravitational law as described in section 2.4. This result is shown in Figure 5. Here we initialized the Earth with a distance of 1AU from the Sun with a velocity slightly higher than circular velocity, namely 6.7AU/Yr . The system was simulated for one year using 10000 timesteps per year. Using a

4. DISCUSSION

As seen in the orbits in Figure 1, the Verlet method keeps the Earth in a circular object, while the Euler method seems to increase the total energy of the system as its orbital radius increases with time. This is expected behaviour, as Verlet is known to be better at conserving energy than Euler. This observation also consistent with Figure 2, 3 and 4. An interesting detail in the discrep-

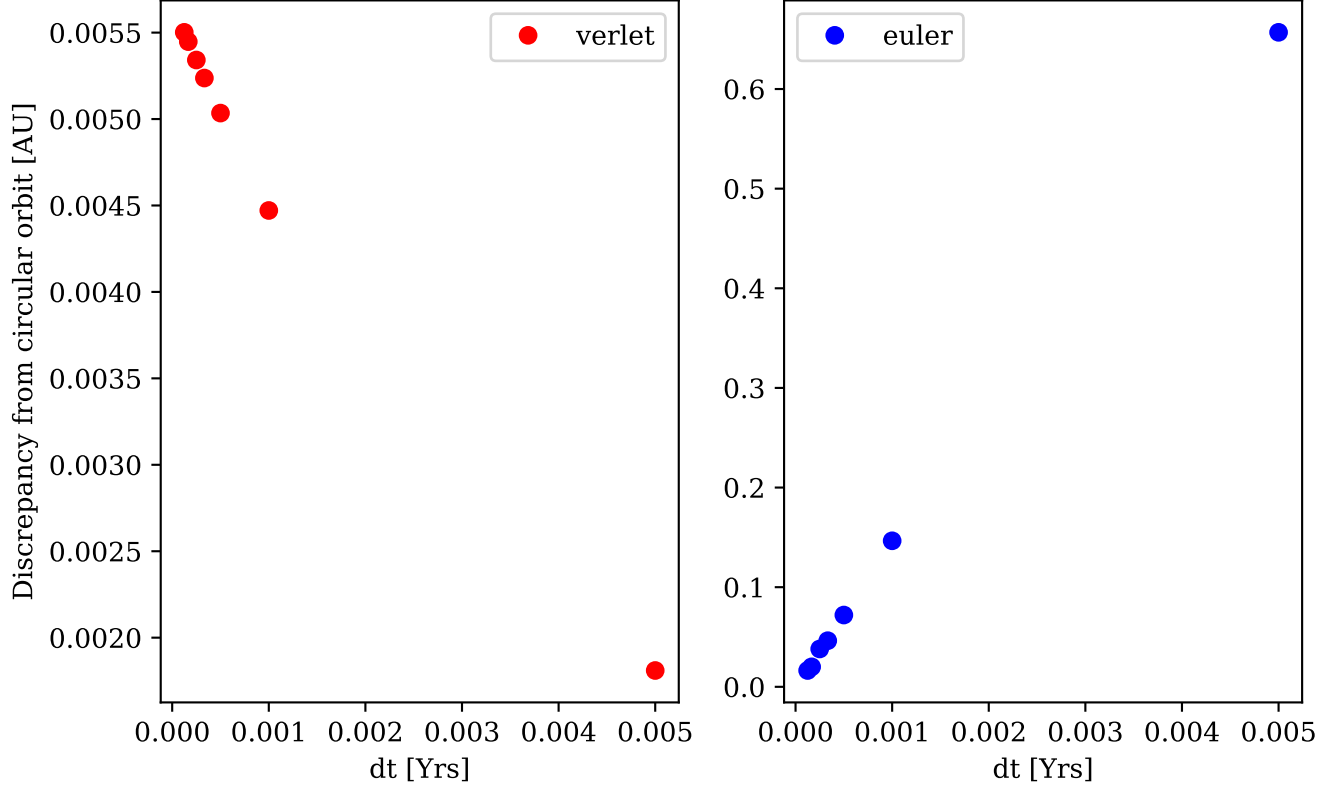


Figure 2. Errors Euler and Verlet

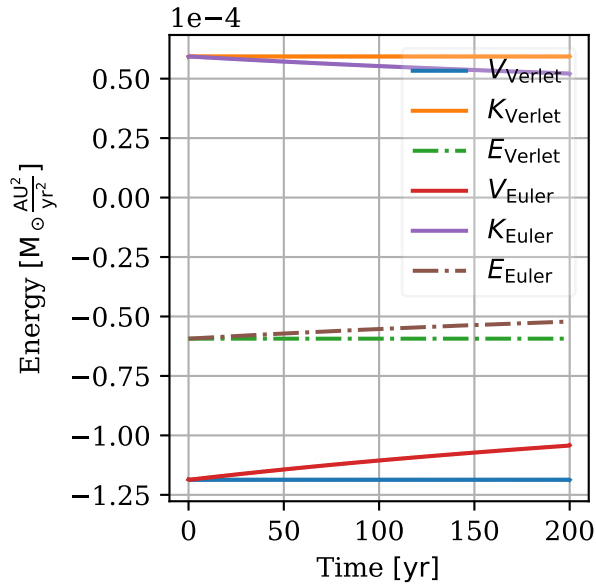


Figure 3. Energies for Euler and Verlet

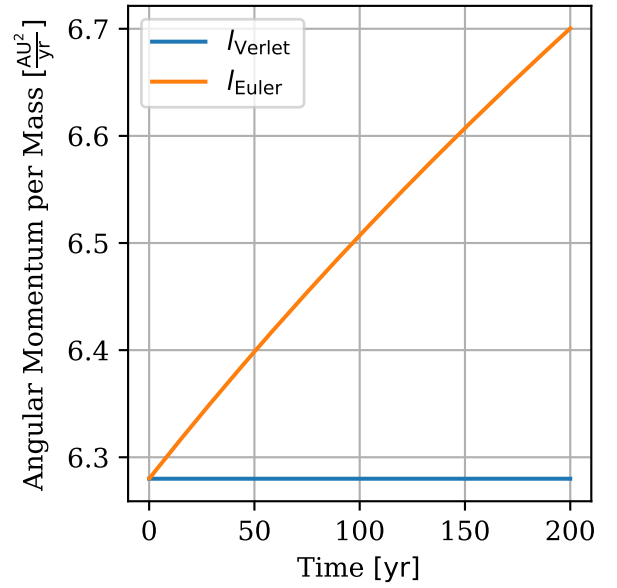


Figure 4. Angular momentum for Euler and Verlet.

ancies shown in Figure 2 is that the error increases with smaller time-steps within the range shown. This makes sense as errors in numerical schemes can be decomposed

into

$$\text{err}_{\text{tot}} = \text{err}_{\text{Taylor}} + \text{err}_{\text{Numerical}}, \quad (23)$$

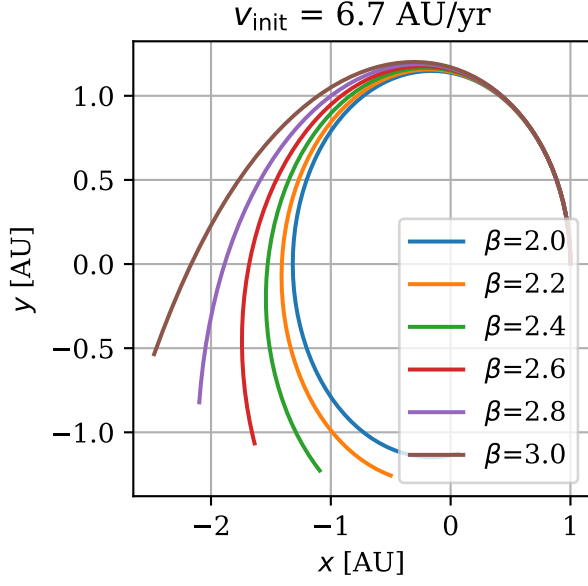


Figure 5. Trajectory Earth Sun different β .

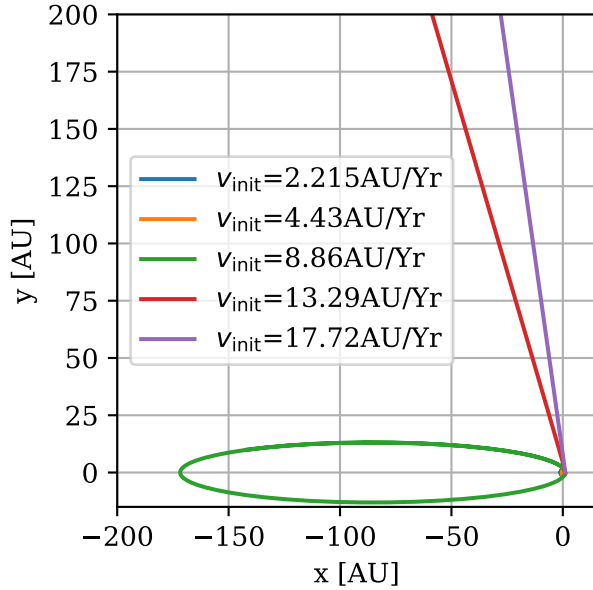


Figure 6. Different velocities for Earth Sun system.

where $\text{err}_{\text{Taylor}}$ is the error from the Taylor series used to derive the numerical scheme and $\text{err}_{\text{Numerical}}$ is the error caused by numerical round off. What is likely happening here is that for Verlet $\text{err}_{\text{Taylor}} \ll \text{err}_{\text{Numerical}}$, and the numerical round off error increases with decreasing time step. Verlet is clearly better suited than Euler for this kind of system.

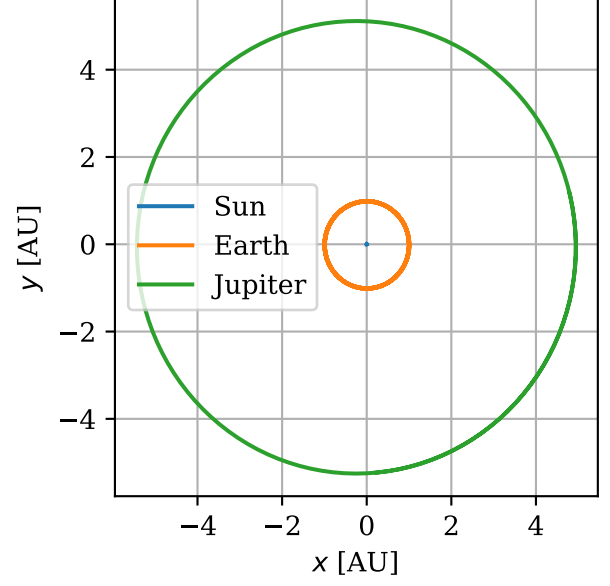


Figure 7. Jupiter normal weight

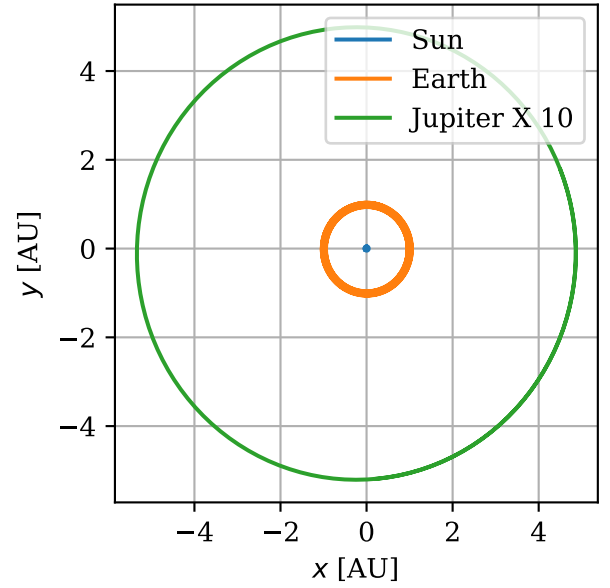


Figure 8. Jupiter ten times size

Figure 5 seems to be consistent with Bertrand's theorem, showing that only the Sun-Earth-system with gravity $F_g \propto R^{-2}$ has a closed orbit. The Earth seems to escape the gravitational pull of the Sun when $\beta > 2$, as the gravitational pull would be weaker at this distance. One could however expect that at a smaller distance, let's say if we were to simulate a Sun-Mercury-system, the force could increase for $\beta > 2$ as $R < 1$ AU.

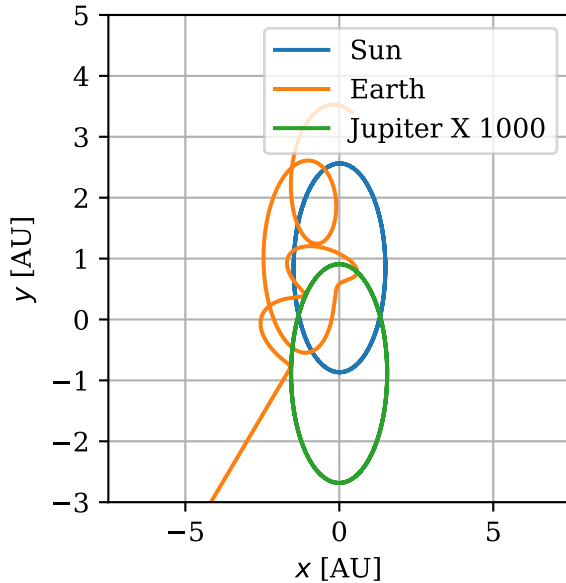


Figure 9. Jupiter 1000 times size

The escape velocity mention stuff here maybe! XD

Increasing the mass of Jupiter in the Sun-Earth-Jupiter-system makes the system behave increasingly chaotically, especially at $1000 \cdot M_{\text{Jupiter}}$. In Figure 9 Jupiter has a mass very similar to M_{\odot} , meaning the system devolves into a chaotic three body system. At one point in time the Earth gets very close to Jupiter, causing it to accelerate and escape the system completely. This result may be non-physical, as we have not implemented any collision effects in our solver and the Earth may have actually hit Jupiter here.

5. CONCLUSION

REFERENCES

- Goldstein, H., Charles, P., & Safko, J. 2001, Classical Mechanics, Addison Wesley,
https://detritus.fundacioace.com/pub/books/Classical_Mechanics_Goldstein_3ed.pdf, Visited: 12.12.2019
- Holmes, M. H. 2007, Introduction to Numerical Methods in Differential Equations, Springer-Verlag New York.
<https://books.google.no/books?id=k53dvgEACAAJ>
- Jensen, M. H. 2015, Computational Physics, Lecture notes Fall 2015, , , <https://github.com/CompPhysics/ComputationalPhysics/blob/master/doc/Lectures/lectures2015.pdf>, Visited: 7.11.2019
- Jensen, M. H. 2019, Project 5, deadline December 15, Computational Physics I FYS3150/FYS4150, Norway: University of Oslo, <http://compphysics.github.io/ComputationalPhysics/doc/Projects/2019/Project5/SolarSystem/html/SolarSystem.html>, Visited: 12.12.2019
- Leinaas, J. 2018, Classical Mechanics and Electrodynamics, World Scientific Publishing Company Pte. Limited.
<https://books.google.no/books?id=k53dvgEACAAJ>
- NASA. 2019, HORIZONS Web-Interface, , , <https://ssd.jpl.nasa.gov/horizons.cgi#top>, Visited: 12.12.2019

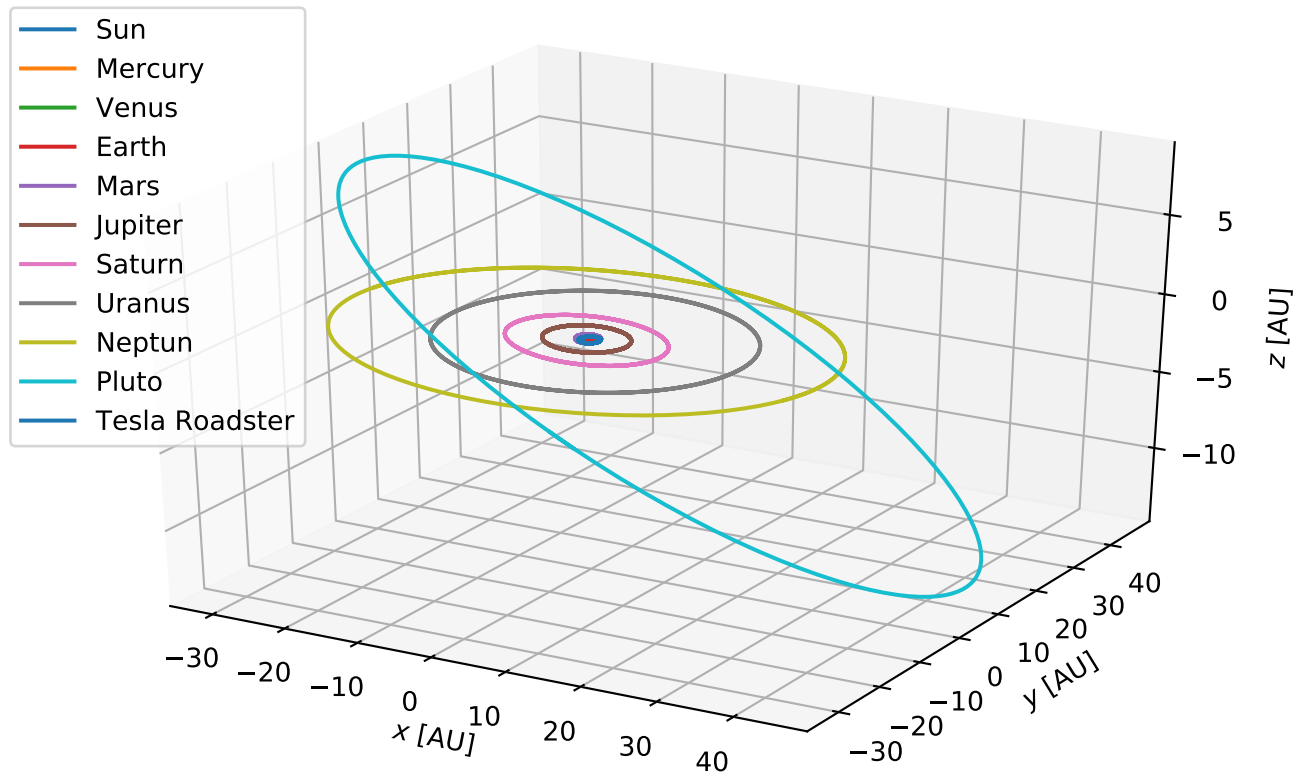


Figure 10. Full solar system

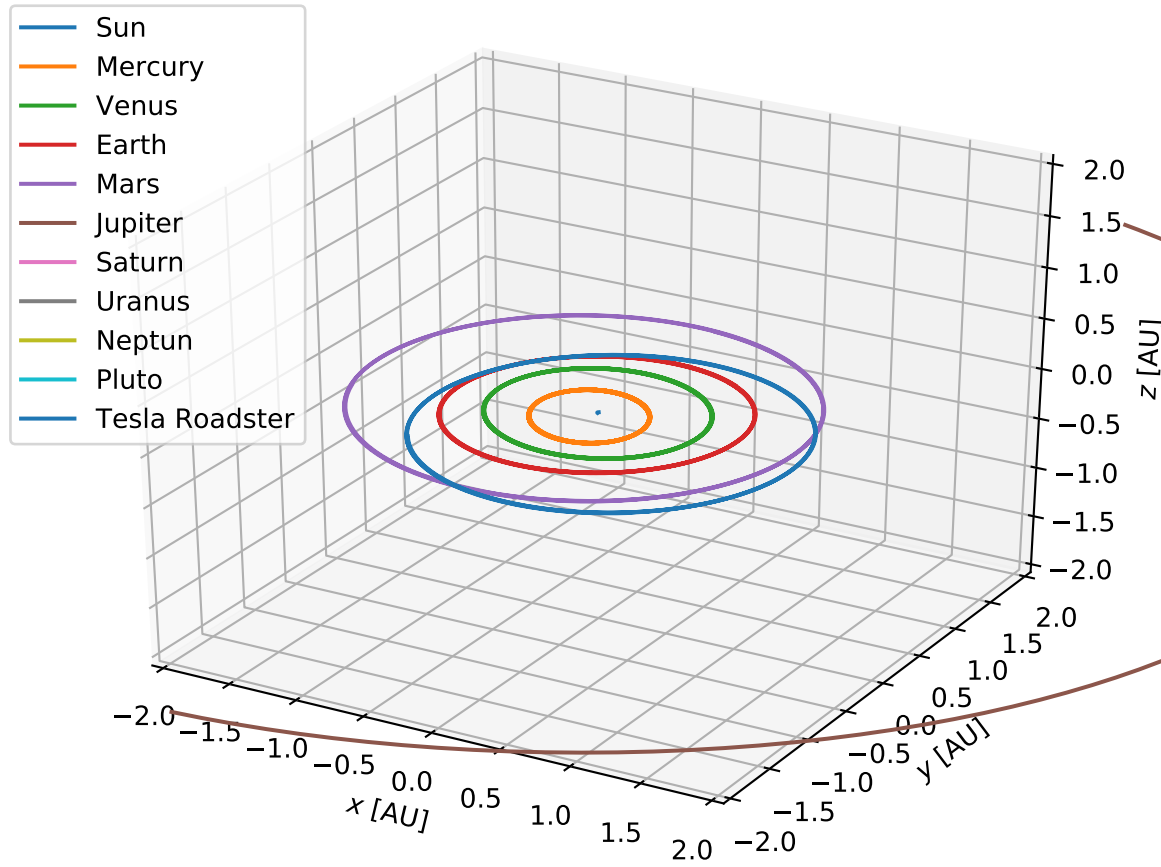


Figure 11. Zoom-in of full solar system