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SIMULATION OF THE SOLAR SYSTEM

Abstract. The article offers calculations and visualization of trajectories of solar system planets done by using the MATLAB software. It contains materials such as Kepler's laws, orbital parameters of planets, formulation of the problem, listings of programs, the model of the solar system and the trajectory of the planet Mars motion in a heliocentric frame of reference during the observation time of one year and ten years. The submitted drawing of the solar system model shows that all planets move along an ellipse, in one of the foci of which there is the Sun as the center of gravity.

From the presented trajectory of Mars in Copernican heliocentric system it is seen that one year observation reveals practically no retrograde motion of the planet but ten years observation makes such motion noticeable. Usually planets move in the sky in a forward direction from the West to the East. Near the opposition the planet changes the direction of its motion and moves in inverse direction from the East to the West, i.e. Mars is in a retrograde (backward) motion. The retrograde motion of Mars with respect to Earth is explained on the base of heliocentric model of the solar system.

Results of this article are used on the practical classes on theoretical mechanics and on the laboratory classes on the discipline "Modeling the physical phenomena".

Key words: solar system, Kepler, trajectory, ellipse, retrograde (backward) motion.

Nowadays all educational institutions of Kazakhstan are provided with computer hardware and software, interactive boards and internet. Almost all teachers have completed language and computer courses for professional development. Hence the educational institutions have all conditions for using computer training programs and models for performing computer laboratory works. In recent years the new computer system of carrying out mathematical calculations MATLAB is being widely used in many universities and engineering institutions throughout the world [1-7]. Unfortunately, the numerical calculations carried out by students are often done by means of the calculator. Modern computers are frequently used only for presentation of the work. Actually students should be able not only to solve these or other engineering problems, but also do it by using modern methods, that is, using personal computers.

Students of the physics specialties 5B060400 and 5B011000 successfully master the discipline “Computer modeling of physical phenomena” which is the logical continuation of the disciplines “Information technologies in teaching physics” and “Use of electronic textbooks in teaching physics”. The aim of this discipline is to study and learn the program language of the MATLAB system, acquaintance with its huge opportunities for modeling and visualization of physical processes.

In our early works [8-23] we used the MATLAB system for modeling and visualization of physical processes related with mechanics, molecular physics, electromagnetism and quantum physics. This software has enabled us to solve ordinary differential equations (ODE), visualize equipotential lines of charged conductors system, describe the motion of charged particles in electric, magnetic and gravitational fields and etc.

The present article is devoted to calculation and visualization of trajectories of solar system planets, the motion path of Mars in the heliocentric system of reference by using the package of MATLAB applied programs.

Formulation of the problem. The heliocentric model of the solar system based on the idea that the Earth and planets move around the Sun was presented by the Polish astronomer Nicolas Copernicus in his book "About Rotation of Celestial Spheres" in 1543. Before him the ideas about heliocentric system were found in the works of a number of the Greek, Arab and Indian scientists. Johannes Kepler in his work "New astronomy" written in 1609 formulated the laws of motion of planets, defined the shape of their orbits and established mathematical relationship between their geometrical parameters and periods of their motion.

Orbital parameters of planets						
Name	Semimajor axis [a.u]	Eccentricity	Inclination to the ecliptic [degrees]	Revolution period [days]	Axis tilt [degrees]	Orbital speed [km/s]
Mercury	0.38709831	0.205631752	7.004986389	87.96843362	0.00	47.87
Venus	0.72332982	0.006771882	3.394661944	224.6954354	177.36	35.02
Earth	1.000001018	0.016708617	0	365.24218985	23.45	29.79
Mars	1.523679342	0.09340062	1.849726389	686.92970957	25.19	24.13
Jupiter	5.202603191	0.048494851	1.303269722	4330.595765	3.13	13.06
Saturn	9.554909596	0.055508622	2.488878056	10746.94044	25.33	9.66
Uranus	19.21844606	0.046295899	0.77319611	30588.74035	97.86	6.8
Neptune	30.11038687	0.008988095	1.7699522	59799.90046	28.31	5.44
Pluto	39.5181762	0.245938782	17.12259917	90738.995	122.52	4.74

The laws of motion of planets were obtained as a result of a large number of precise astronomical observations. Let's consider three laws of Kepler:

1. The orbits of the planets are elliptical with the Sun at one focus of the ellipse.
2. The radius vector of each planet sweeps out equal areas in equal time.
3. The ratio of the square of each planet's sidereal period to the cube of the semimajor axis of its orbit is a constant for all the planets.

Here is the listing of the program:

```
>> Planet= zeros(9,3);
>> % Semimajor axis (a.u.) Eccentricity; Revolution period (days)
>> Planet(1,:)=[0.38709831; 0.205631752; 87.96843362]; % Mercury
>> Planet(2,:)=[0.72332982; 0.006771882; 224.6954354]; % Venus
>> Planet(3,:)=[1.000001018; 0.016708617; 365.24218985]; % Earth
>> Planet(4,:)=[1.523679342; 0.09340062; 686.92970957]; % Mars
>> Planet(5,:)=[5.202603191; 0.048494851; 4330.595765]; % Jupiter
>> Planet(6,:)=[9.554909596; 0.055508622; 10746.94044]; % Saturn
>> Planet(7,:)=[19.21844606; 0.046295899; 30588.74035]; % Uranus
>> Planet(8,:)=[30.11038687; 0.008988095; 59799.90046]; % Neptune
>> Planet(9,:)=[39.5181762; 0.245938782; 90738.995]; % Pluto
>> Cg= {'m', 'b', 'g', 'r','k'};
>> % drawing the orbits of planets
>> figure('Color',[1 1 1]);
>> ksi=linspace(0,2*pi,500);
>> hold on;
>> plot(0,0,'ok');
>> for iCurP=1:9
>> a=Planet(iCurP,1);
```

```
>> e=Planet(iCurP,2);
>> T=Planet(iCurP,3);
>> t=(0.5*T/pi)*(ksi-e.*sin(ksi));
>> x=a.*(cos(ksi)-e);
>> y=a*sqrt(1-e^2).*sin(ksi);
>> plot(x,y);
>> %plot(x,y,Cg{iCurP-4});
>> %pause(2)
>> end
```

The result is presented in the figure 1.

Figure 1 presents the model of the solar system. The diagrams show that each planet moves along the ellipse with the Sun at one focus of the ellipse. The Sun is the center of gravity and any such model is always developed with violation of the scale.

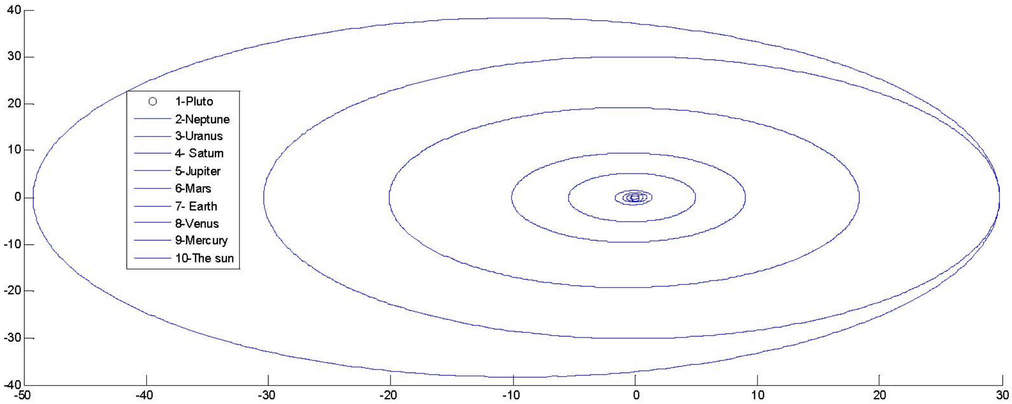

Figure 1 – Trajectories of motion of solar system planets

Calculation and visualization of Mars trajectory in the heliocentric system. Since the ancient times the astronomy tried to solve the mystery of retrograde motions of planets. Such motions are especially noticeable for outer planets. Usually planets move in the sky in a forward direction from the West to the East. Near the opposition the planet changes the direction of its motion and moves in inverse direction from the East to the West. The retrograde motion of the Mars is shown in figure 2.

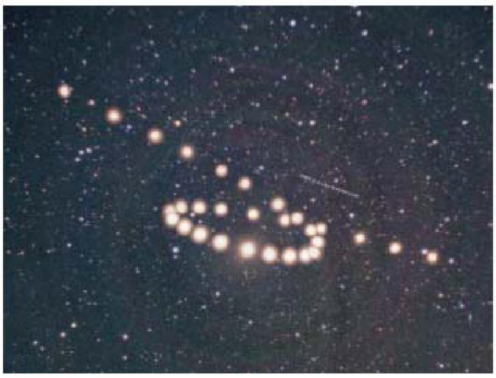

Figure 2 – The retrograde motion of the Mars

Let us draw the trajectory of the Mars in the geocentric reference system being at the same time within a heliocentric system. In other words we will answer the question: what will be the path of the Mars in the sky for the observer on the Earth? The position vectors describing the motion of the Earth and Mars in the heliocentric system and the position vector describing the motion of the Mars in the geocentric system are connected by a simple relationship:

$$\vec{r}_{SE} + \vec{r}_{EM} = \vec{r}_{SM}$$

The abbreviation in the subscript SE means the Sun and Earth, EM means for the Earth and Mars, SM means for the Sun and Mars. Knowing the position of planets at the same time, it is possible to define the position vector of Mars in the geocentric reference system:

$$\vec{r}_{EM} = \vec{r}_{SM} - \vec{r}_{SE}$$

The listing of the program is:

>> R1=1.496*10^8;% input the radius of the Earth's orbit

>> T1=365.24; % input the period of the Earth revolution round the Sun in days

>> Am=2.28*10^8; % input the radius of Mars's orbit

>> Tm=689.98; % input the period of Mars revolution round the Sun in days

>> E=0.093; % eccentricity of Mars's orbit

>> Np=1000; % number of points for one revolution of Mars round the Sun

>> K=9; % number of revolutions of Mars round the Sun

>> dski=(2*pi)/Np*K; % calculation of the step $\Delta\epsilon$ of the variable parameter ϵ

>> ksi=0:dski:2*pi; % calculation of values of vector coordinates ϵ_i, % calculation of values of coordinates $T_i = r(\epsilon_i)$

>> T=Tm/(2*pi)*(ksi-E*sin(ksi)); % calculation of instantaneous values of the % Mars's radius-vector Ox component

>> Xm=Am*((1-E.^2).^0.5)*sin(ksi); % calculation of instantaneous values of % the Earth's radius-vector Ox component

>> Xz=R1*cos(2*pi*T/T1); % calculation of instantaneous values of the Earth's % radius-vector Oy component

>> Yz=R1*sin(2*pi*T/T1); calculation of instantaneous values of Mars's % radius-vector Oy component in the reference system connected with the Earth.

>> Xotn=Xm-Xz; % calculation of instantaneous values of the distance between % the Earth and Mars

>> Ym=Am*((1-E.^2).^0.5)*sin(ksi);

>> Xm=Am*(cos(ksi)-E);

>> Xotn=Xm-Xz;

>> Yotn=Ym-Yz;

>> plot(Xotn,Yotn,...% the orbit of Mars

>>'k',...% the initial position of Mars 'MarkerEdgeColor','b','MarkerFaceColor','g','MarkerSize',5);

The result is presented in the figure 3.

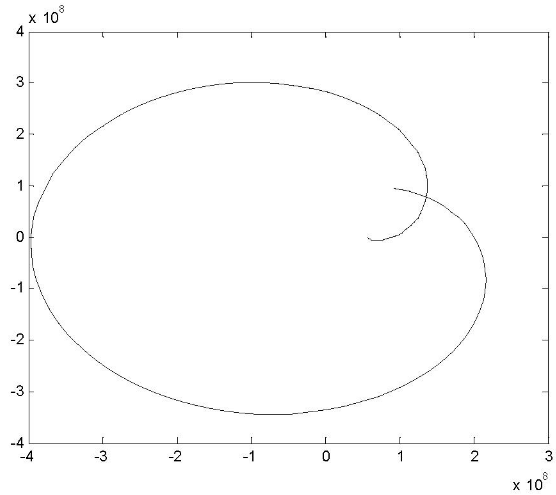

Figure 3 – The trajectory of the Mars (observation time is one year)

During one year observation the retrograde motion of Mars is imperceptible therefore for obtaining this retrograde motion we will increase the observation time up to 10 years.

The listing of the program is:

```
>> R1=1.496*10^8;
>> T1=365.24;
>> Am=2.28*10^8;
>> Tm=689.98;
>> E=0.093;
>> Np=10000;
>> K=9;
 dski=(2*pi)/Np*K;
 ksi=0:dski:2*pi;
T=10*Tm/(2*pi)*(ksi-E*sin(ksi));
Xm=Am*((1-E.^2).^0.5)*sin(ksi);
Xz=R1*cos(2*pi*T/T1);
Yz=R1*sin(2*pi*T/T1);
Xotn=Xm-Xz;
Ym=Am*((1-E.^2).^0.5)*sin(ksi);
Xm=Am*(cos(ksi)-E);
Xotn=Xm-Xz;
Yotn=Ym-Yz;
plot(Xotn,Yotn,...% the orbit of Mars
'k',...% the initial position of Mars
'MarkerEdgeColor','b','MarkerFaceColor','g','MarkerSize',5);
>> Np=10000;
>> K=9;
 dski=(2*pi)/Np*K;
 ksi=0:dski:2*pi;
T=10*Tm/(2*pi)*(ksi-E*sin(ksi));
Xm=Am*((1-E.^2).^0.5)*sin(ksi);
 Xz=R1*cos(2*pi*T/T1);
 Yz=R1*sin(2*pi*T/T1);
 Xotn=Xm-Xz;
 Ym=Am*((1-E.^2).^0.5)*sin(ksi);
 Xm=Am*(cos(ksi)-E);
 Xotn=Xm-Xz;
Yotn=Ym-Yz;
 plot(Xotn,Yotn,...% the orbit of Mars
'k',...% the initial position of Mars
'MarkerEdgeColor','b','MarkerFaceColor','g','MarkerSize',5);
```

The result is presented in the fig.4.

The figure presents the motion of the planet in the sky in the forward direction from west to east and then near the opposition the planet changes the direction of its motion for inverse and moves from east to west (the retrograde motion), i.e. Mars moves along a loop made near the opposition.

Conclusion. Calculations and visualization of trajectories of solar system planets are presented using the MATLAB software. The materials such as Kepler's laws, orbital parameters of planets are applied for simulation the solar system and the trajectory of Mars motion in a heliocentric frame of reference during the observation time of one year and ten years. The submitted drawing of the solar system model shows that all planets move along an ellipse, in one of the foci of which there is the Sun as the center of gravity.

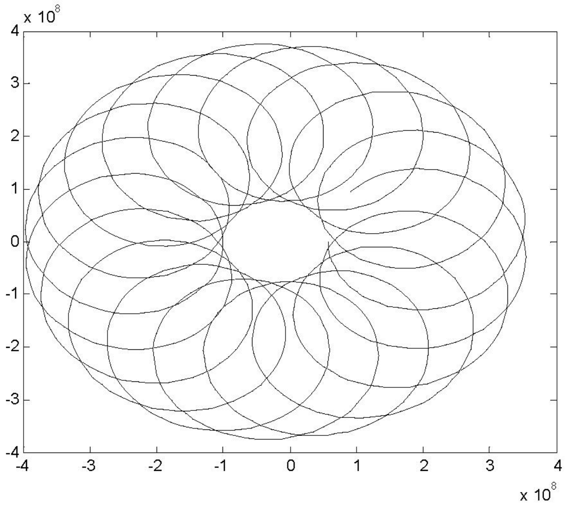

Figure 4 – The trajectory of the Mars (observation time is ten years)

From the presented trajectory of Mars in Copernican heliocentric system it is seen that one year observation reveals practically no retrograde motion of the planet but ten years observation makes such motion noticeable. Usually planets move in the sky in a forward direction from west to east. Near the opposition the planet changes the direction of its motion and moves in inverse direction from east to west, i.e. Mars is in a retrograde (backward) motion. The retrograde motion of Mars with respect to Earth is explained on the base of heliocentric model of the solar system.

Results of this article are used on the practical classes on theoretical mechanics and on the laboratory classes on the discipline "Modeling the physical phenomena".

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КҮН ЖҮЙЕСІНІҢ МОДЕЛІН ҚҰРУ

Аннотация. Күн жүйесінің планеталарының қозғалысын MATLAB бағдарламалық ортасында есептеу мен бейнелеу ұсынылады. Кеплер заңдары, планеталардың орбиталық параметрлері, есептің шарттары, бағдарламаның кодтары, күн жүйесінің моделі және Марс планетасының гелиоцентрлік санақ жүйесіндегі 4 жыл және 10 жыл бақылау кезіндегі қозғалыс траекториялары келтірілген. Келтірілген суреттерден күн жүйесінің моделін байқаймыз-барлық планеталар бір фокусында тарту центрі-Күн орнасқан эллипс бойында қозғалаынын байқаймыз.

Марстың қозғалған траекторысының 1 жылдығында оның кері қозғалысы байқалмайды, ал оның кері қоғалысы уақытты 10 жылға дейін ұзартқанда байқалады. Әдетте планета аспанда батыстан шығысқа қарай тікелей қозғады. Ал қарсылас тұсқа жақын жерде ол қозғалыс бағытын кері өзгертіп шыңыстан батысқа қарай қозғалады, яғни кері қозғалыс жасайды. Марстың осындай кері қозғалысын күн жүйесінің моделі бойынша түсіндіріледі.

Мақаланың нәтижелері теориялық механиканың практикалық сабағында және «Физикалық құбылыстарды молелдеу» пәнінің зертханалық сабақтарында қолданылады.

Түйін сөздер: Күн жүйесі, Кеплер, траектория, эллипс, кері қозғалыс.

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МОДЕЛИРОВАНИЕ СОЛНЕЧНОЙ СИСТЕМЫ

Аннотация. Предлагается расчеты и визуализация траекторий движения планет солнечной системы в программной среде MATLAB. Приводятся законы Кеплера, орбитальные параметры планет, постановка задачи, листинги программ, модель солнечной системы и траектория движения планеты Марс в гелиоцентри-

ческой системе отсчета за время наблюдения 1 год и 10 лет. Из представленного рисунка – модели солнечной системы видно, что все планеты движутся вдоль эллипса, в одном из фокусе которого находится Солнце – центр притяжения.

Из представленной траектории Марса в гелиоцентричесой системе за время наблюдения 1 год незаметно попятное движение планеты и при увеличении времени наблюдения до 10 лет такое движение становится заметным. Обычно планеты движутся по небосклону в прямом направлении с запада на восток. Вблизи противостояния планета меняет направление движения на обратное и движется с востока на запад, т.е. наблюдается попятное (возвратное) движение Марса. Попятное движение Марса на небосводе Земли находит свое объяснение в рамках гелиоцентрической модели солнечной системы.

Результаты данной статьи используются на практических занятиях по теоретической механике и на лабораторных занятиях по дисциплине «Моделирование физических явлений».

Ключевые слова: Солнечная система, Кеплер, траектория, эллипс, попятное движение.

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