Exam Solution

Course: AE4874 Fundamentals of Astrodynamics
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1 Question 1: Three body problem & Surfaces of Hill

For the circular-restricted three body problem the equation for the Surface of Hill can be derived as:

$$x^2 + y^2 + \frac{2(1-\mu)}{r_1} + \frac{2\mu}{r_2} = C \tag{1}$$

There are 5 Lagrangian points on the Surfaces of Hill.

1.1 1a

What do the parameters of the given equation mean, and explain the physical meaning of the Surfaces of Hill.

First sketch the circular-restricted three body problem:

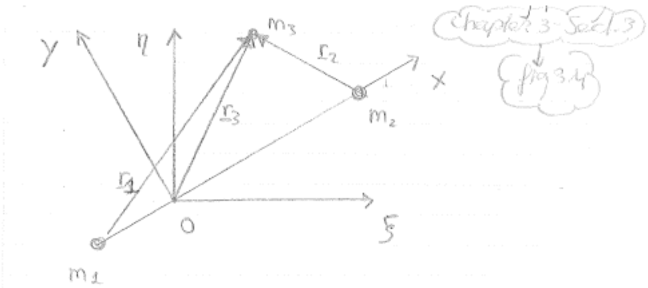

Figure 1: Circular-restricted three body problem

Parameters:

- x is the x-coordinate of body 3, so x_3
- y is the y-coordinate of body 3, so y_3
- r_1 is the length of the position vector from body 1 to body 3
- r_2 is the length of the position vector from body 2 to body 3
- μ is the mass of body 2
- $1-\mu$ is the mass of body 1
- C is the Jacobian Constant

The Surfaces of Hill are the surfaces in the XYZ-space on which the velocity of the third body is zero. This is the case when in equation 1 V equals zero.

1.2 1b

Using clear sketches, provide a qualitative analysis of the shape and size of the Surfaces of Hill for changing values of C, and indicate the Lagrange points in the sketches.

$$r_3^2 + \frac{2(1-\mu)}{r_1} + \frac{2\mu}{r_2} = C \tag{2}$$

If we look at the relevant equation, we can see that there for large values of C, there are 3 solutions:

1. r_3 is very large, hence p_3 is far away from p_1 and p_2. The radius of the circle will be $\sqrt{C}$.
2. r_1 is very small, hence p_3 is near p_1
3. r_2 is very small, hence p_3 is near p_2

When the value of C starts to decrease, we may observe three things. Either r_3 decreases, or r_1 increases, or r_2 increases. The resulting circles/ovals can be sketched in the XY-plane. We may find the Lagrange points at the points where the ovals intersect. This can be seen in the following figure:

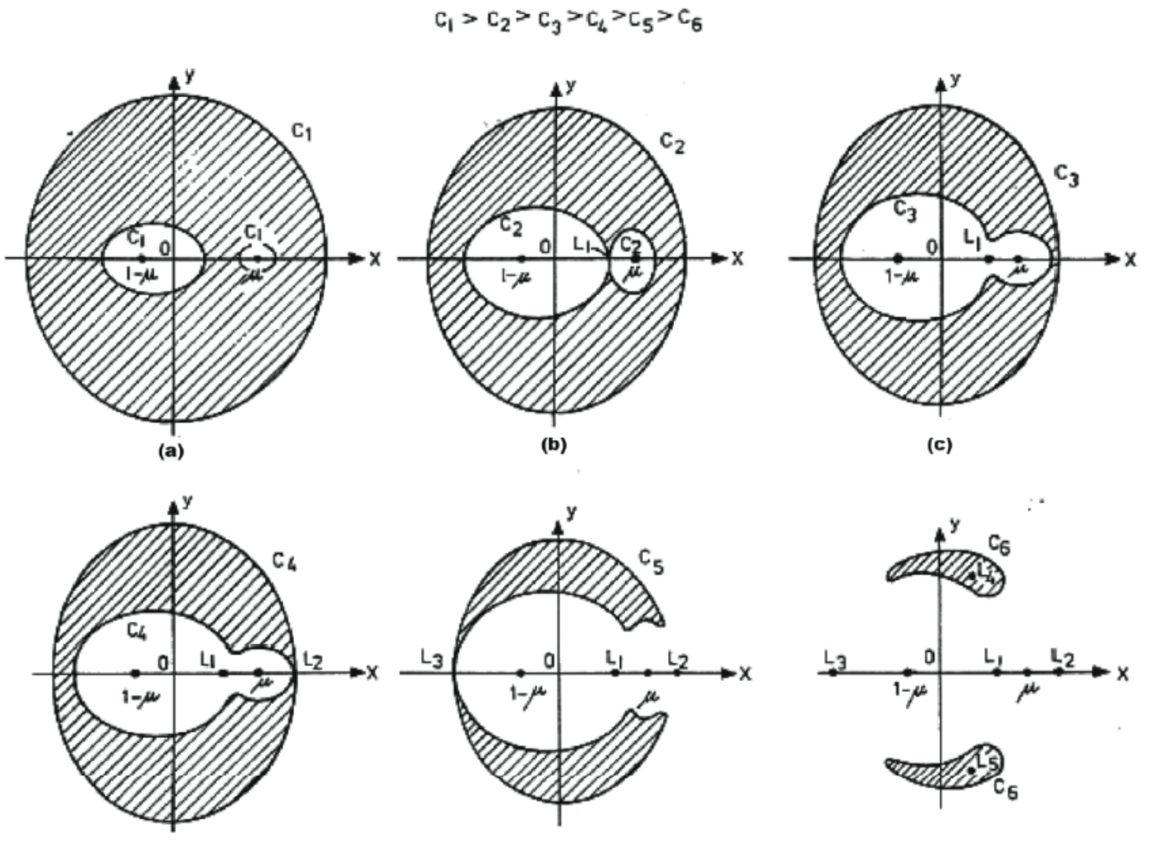

Figure 2: Surfaces of Hill for various values of C

The Lagrange point L_1 appears first, at the point where the ovals around p_1 and p_2 intersect. Next, L_2 and L_3 appear when the outer Surface of Hill intersects with the oval around p_2 and p_1 respectively. As C decreases further, it will look like Figure 2(f). The two leftover areas shrink until they vanish in points L_4 (above) and L_5 (below).

1.3 1c

Explain the physical interpretation of the Langrange points.
The Lagrange points are those points where not only velocity V is zero, but the net acceleration is also zero. If body 3 were to be placed at such a point, without any residual velocity, it would remain at this point.

1.4 1d

It is possible to bring a spacecraft in a quasi-periodic "slowly changing elliptic" orbit around a Langrange point, also known as a Halo orbit. Give for all five Lagrange points a sketch of the orbit of a spacecraft around the point, and indicate the direction of motion of the vehicle.

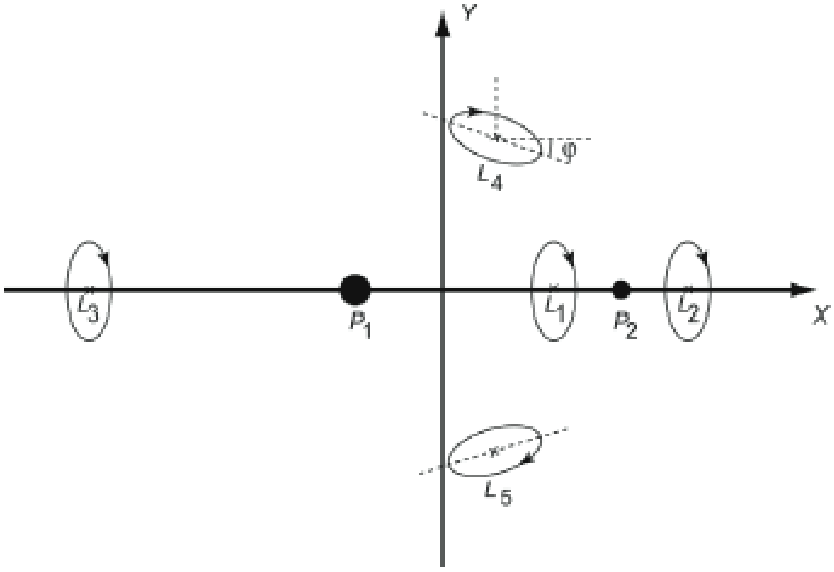

Figure 3: Halo orbits around all five Lagrange points

In general, for a stable orbit around L_4 and L_5, ϕ is around 30 degrees.

1.5 1e

Provide an example of a possible application for such a Halo orbit.
For missions to the far side of the moon, radio communication can be troublesome, as there is a moon in the way. A relay communication satellite around L_2 of the Earth-Moon system would solve this problem, as it is often able to see the far side of the moon and the Earth at the same time, provided the orbit radius is large enough.

2 Question 2

Consider a body that moves in an low-eccentric elliptic orbit around the sun. You may assume that the body is only subject to the gravitational attraction of the sun, described by gravitation potential, and the radiation pressure of the sunlight. The equations of motion of this body are:

$$\begin{aligned} \ddot{r} - r\dot{\theta}^2 &= -\frac{\mu}{r^2} + \frac{F}{m}\sin(\delta) \\ \frac{d}{dt}\left(r^2\dot{\theta}\right) &= \frac{F}{m} r\cos(\delta) \end{aligned} \tag{3}$$

where:

$$F = C_R \frac{WS}{c} \tag{4}$$

If one assumes that the sunlight is radiated in a radially symmetrical way, and that the orbiting body is spherical, then the acceleration of the body because of radiation pressure can be formulated as:

$$\frac{F}{m} = \frac{3}{4}\frac{C_R W_s R_s^2}{c\rho R}\frac{1}{r^2} \tag{5}$$

for a given body follows that:

$$\frac{F}{m} = \frac{\alpha}{r^2} \tag{6}$$

where α is a constant.

2.1 2a

Indicate what the parameters in equations 3, 4, and 5 mean.
Parameters:

- $\ddot{r}$ is the radial acceleration of the body in orbit
- r is the radial distance of the body in orbit w.r.t. the CoM of the sun
- $\dot{\theta}$ is the angular velocity of the body in orbit w.r.t. the sun
- μ is the gravitational parameters of the sun (assuming $m_{sun} \gg m_{body}$)
- F is the force due to the solar radiation pressure action on the body in orbit
- m is the mass of the body in orbit
- δ is the angle of F w.r.t. the tangential velocity of the body in orbit (see figure 4)

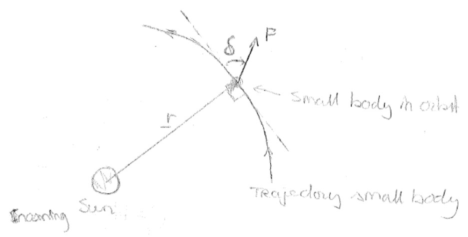

Figure 4: Definition of angle δ

Furthermore:

- C_R is the reflectivity coefficient of the body in orbit
- W is the power density of the incoming beam
- W_S is the power density of the sun
- S is the illuminated surface area of the body in orbit
- c is the speed of light
- R_S is the radius of the sun
- ρ is the density of the body in orbit
- R is the radius of the spherical body in orbit
- α is a constant defined as $\frac{3C_R W_S R_S^2}{4c\rho R}$

Finally, what the terms mean:

- $\ddot{r}$ is the acceleration of the body in orbit
- $(-r\dot{\theta})$ is the centrifugal acceleration on the body in orbit, caused by the rotation of the sun
- $\frac{\mu}{r^2}$ is the gravitational acceleration of the sun
- $F/m \cdot sin(\delta)\, and\, F/m \cdot cos(\delta)$ are accelerations due to the solar radiation pressure
- $r^2\dot{\theta}$ is the angular momentum of the body in orbit
- $\frac{d}{dt}(r^2\dot{\theta})$ is the change of angular momentum over time.

2.2 2b

Explain why generally for the computation of the effects of solar radiation pressure on the orbit of the body, a doppler-term and an abberation-term must be taken into account. These phenomena can be described by:

$$W' = W\left(1 - \frac{\dot{r}}{c}\right) \quad ; \quad \gamma = \frac{r\dot{\theta}}{c} \tag{7}$$

The energy of a photon can be represented by

$$E_{ph} = h \cdot f \tag{8}$$

where h is the Planck constant and f the frequency of the photon. Since it was assumed that the sun emits energy in a radially symmetric manner, if the body is in a circular orbit, the frequency of the body will be unchanged. If the radius of the body in orbit increases (because of increasing $\ddot{r}$) the frequency of the energy will decrease compared to if the body was in a circular orbit. Therefore, the incoming power density will decrease. If the radius of the body in orbit decreases due to decreasing $\ddot{r}$, the frequency of the incoming energy will increase w.r.t. the body in a circular orbit and therefore the power density will increase. These two effects are the doppler-effect and can be described by $W' = W\left(1 - \frac{\dot{r}}{c}\right)$.

The aberration effect is the phenomenon that the incoming beam of the sun falls under a small angle onto the body in orbit, due to the travel time of the incoming beam. The explanation of this phenomenon is more clearly indicated with the following sketches: At t_0, the sunlight leaves the surface of the sun and travels towards the body in orbit.

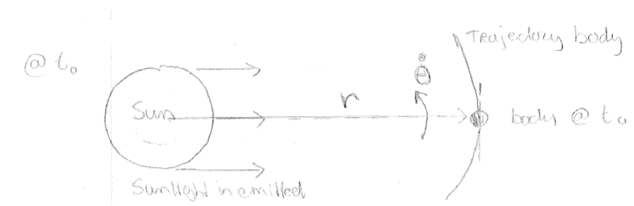

Figure 5: Situation at t_0

Then, at $t_0 + \Delta t$, this sunlight reaches the body in orbit, under an angle γ.

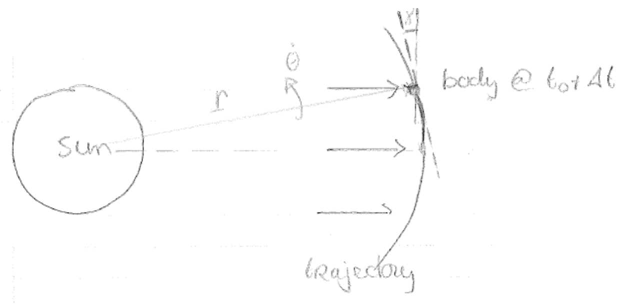

Figure 6: Situation at $t_0 + \Delta t$

This incoming angle can be described by:

$$\gamma = \frac{r \cdot \dot{\theta}}{c} \tag{9}$$

2.3 2c

Derive how with the effects of question 2b, a first-order approximation of equations 3 can be written as:

$$\begin{aligned} \ddot{r} - r\dot{\theta}^2 &= -\frac{\mu - \alpha}{r^2} - \frac{\alpha \dot{r}}{cr^2} \\ \frac{d}{dt}\left(r^2\dot{\theta}\right) &= -\frac{\alpha\dot{\theta}}{c} \end{aligned} \tag{10}$$

Using these equations, provide a description of the two effects of the radiation pressure on the motion of the orbiting body (Poynting-Robertson effect).

Filling in the doppler-term into the given relation for F/m:

$$\frac{F}{m} = \frac{3}{4}\frac{C_R \cdot W_s' \cdot R_S}{C \cdot \rho \cdot R} \cdot \frac{1}{r^2} = \frac{3}{4}\frac{C_R \cdot W_s \cdot R_S}{C \cdot \rho \cdot R}\left[1 - \frac{\dot{r}}{c}\right] \cdot \frac{1}{r^2} \tag{11}$$

and so:

$$\frac{F}{m} = \frac{\alpha}{r^2}\left[1 - \frac{\dot{r}}{c}\right] \tag{12}$$

For the aberration effect, the angle δ is increased by angle γ. If we assume that the effect of $\delta \approx 90^{/circ}$:

$$\begin{aligned} \sin(\delta + \gamma) &\approx \sin\left(\frac{\pi}{2} + \gamma\right) = \cos(\gamma) \\ \cos(\delta + \gamma) &\approx \cos\left(\frac{\pi}{2} + \gamma\right) = -\sin(\gamma) \end{aligned} \tag{13}$$

If we further assume that the aberration angle γ is small, we get:

$$\begin{aligned} \sin(\gamma) \approx \gamma \quad andso \quad \sin(\delta) \approx 1 \\ \cos(\gamma) \approx 1 \quad andso \quad \cos(\delta) \approx -\gamma \end{aligned} \tag{14}$$

If we apply the previous to the equations of motion:

$$\begin{aligned} \ddot{r} - r \cdot \dot{\theta}^2 &= -\frac{\mu}{r^2} + \frac{\alpha}{r^2}\left[1 - \frac{\dot{r}}{c}\right] \cdot 1 = -\frac{(\mu - \alpha)}{r^2} - \frac{\alpha \cdot \dot{r}}{c \cdot r^2} \\ \frac{d}{dt}\left(r^2 \cdot \dot{theta}\right) &= \frac{\alpha}{r^2}\left[1 - \frac{\dot{r}}{c}\right] \cdot -\gamma = -\frac{\alpha \cdot \dot{\theta}}{c} + \frac{\dot{r} \cdot r \cdot \dot{\theta} \cdot x}{r \cdot c^2} \approx -\frac{\alpha \cdot \dot{\theta}}{c} \end{aligned} \tag{15}$$

The Poynting-Robertson effect describes the tendency of the solar radiation pressure to reduce the acceleration due to the gravitational attraction of the sun. It causes a drag-like force that reduces the acceleration in the radial direction and in the tangential (circumferential) direction.

2.4 2d

As α increases, the effects of radiation pressure on the orbit of the body will increase. Which kinds of bodies will have a large value of α?
If we look at the definition of α:

$$\alpha = \frac{3C_R W_S R_S^2}{4c\rho R} \tag{16}$$

we see that α increases if a body is more reflective (C_R), less dense (ρ) or has smaller radius (R). The speed of light, and the power density and radius of the sun do not depend on the body in orbit.

2.5 2e

It can be shown that generally $\alpha = \mu$ for a value between $R = 0.09/, -/, 7\,\mu m$. In reality, the sun radiates 97% of its energy with wavelengths between $0.3/, -/, 0.9\,\mu m$. What can be said about particles in our solar system whose size is comparable to these wavelengths, and about the fact that we see the sun as a "bright disc", rather than a "blurry light source"?

If a particle has the dimension of order of the wavelength, $\alpha = \mu$. Looking at the first equation of motion, in this case the gravitational attraction is counteracted, so there will only be a 'drag-like' term, which will accelerate the body away from the sun. Since these particles are accelerated away from the sun, the sun can be seen as a clear disk, since the particles are "blown away".

3 Question 3

We consider a movement of a satellite around the Earth. From observation data can be concluded that the orbit of the satellite has a period of $T = 1.85$ hours, and that at a given time t_0 the radial and normal components of the satellite's velocity are given by $\dot{r} = -0.2481$ km/s and $rtheta = 6.5726$ km/s. Furthermore, it is known that the satellite is in a low eccentric orbit ($e < 0.3$).

3.1 3a

From the general equation for an elliptical orbit, derive the following expressions for the radial and normal velocity components:

$$\dot{r} = \frac{\mu}{H} e \sin(\theta) \quad ; \quad r\dot{\theta} = \frac{\mu}{H}(1 - e\cos(\theta)) \tag{17}$$

For a generic elliptic orbit, its radius is described by:

$$r = \frac{p}{1 + e\cos(\theta)} \tag{18}$$

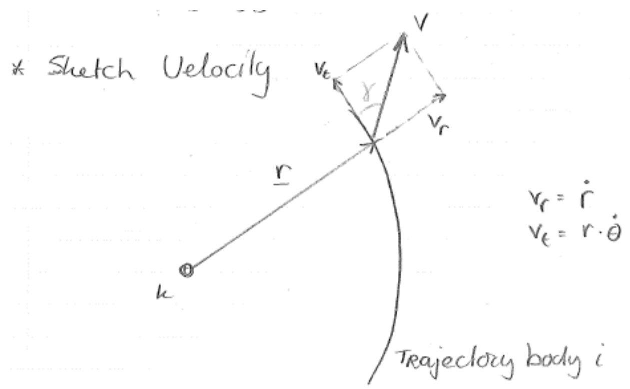

Figure 7: Velocities of a body in orbit.

The radial velocity as defined in figure 7 equals:

$$\dot{r} = V \cdot \sin(\gamma) \quad andso \quad V = \frac{\dot{r}}{\sin(\gamma)} \tag{19}$$

For the tangential velocity, we have:

$$r \cdot \dot{\theta} = V \cdot \cos(\gamma) \quad andso \quad V = \frac{r\dot{\theta}}{\cos(\gamma)} \tag{20}$$

So the flight path angle can be defined as:

$$\tan(\gamma) = \frac{\dot{r}}{r\dot{\theta}} \tag{21}$$

Furthermore, for the angular momentum we can find:

$$\begin{aligned} H = rV_t = r \cdot r \cdot \dot{\theta} = r^2\dot{\theta} = v \cdot r \cdot \cos(\gamma) \\ r \cdot \theta = \frac{H}{r} = \frac{H}{p}[1 + e\cos(\theta)] \end{aligned} \tag{22}$$

Given the definition of the semi-latus rectum, namely that $p = H^2/\mu$, we can rewrite this further:

$$r \cdot \theta = \frac{\mu}{H}[1 + e\cos(\theta)] \tag{23}$$

So for the radial velocity, we get:

$$\begin{aligned} \dot{r} = \frac{d}{dt}(r) = \frac{d}{dt}\left[\frac{p}{1 + e\cos(\theta)}\right] = \frac{d}{dt}\left[\frac{H^2/\mu}{1 + e\cos(\theta)}\right] \\ = \frac{p \cdot \dot{\theta}}{[1 + e \cdot \cos(\theta)]^{-2}} \cdot e\sin(\theta) \end{aligned} \tag{24}$$

$\dot{\theta}$ can be found from the normal velocity to be:

$$\dot{\theta} = \frac{\mu}{H \cdot r}[1 + e\cos(\theta)] \tag{25}$$

Fill this into equation 24 and rewrite using equation 18 to find:

$$\frac{d}{dt}(r) = \frac{\mu}{H} \cdot \frac{1}{r} \cdot \frac{p}{[1 + e\cos(\theta)]} \cdot e\sin(\theta) = \frac{\mu}{H} \cdot e \cdot \sin(\theta) \tag{26}$$

3.2 3b

Using these relations and the provided values of the velocity components at t_0, calculate the eccentricity of the orbit e and the true anomaly θ. An iterative approach must be used. To ensure proper accuracy, every parameter must be calculated to at least 5 decimals.

We start with the second conservation law:

$$A = 1/2H \cdot \Delta t \tag{27}$$

The orbital period is then, given the conservation law, the area of an ellipse, and the definition of the semi-latus rectum, respectively:

$$T = \Delta t = \frac{2A}{H} = \frac{2\pi \cdot a \cdot b}{H} = \frac{2\pi \cdot a \cdot b}{\sqrt{p \cdot \mu}} \tag{28}$$

For the apogee and perigee we have:

$$\begin{aligned} r_{\theta=0^\circ} = r_p &= \frac{p}{1+e\cos(0)} = \frac{p}{1+e} \\ r_{\theta=180^\circ} = r_p &= \frac{p}{1+e\cos(180)} = \frac{p}{1-e} \end{aligned} \tag{29}$$

For the semi-major axis:

$$2a = r_p + r_a = \frac{p}{1+e} + \frac{p}{1-e} = \frac{p(1-e)+p(1+e)}{(1+e)(1-e)} = \frac{2p}{1-e^2} \tag{30}$$

Fill into orbital period T:

$$T = \frac{2\pi \cdot a \cdot b}{\sqrt{a(1-e^2)\mu}} \tag{31}$$

Expression for semi-major axis:

$$\begin{aligned} s = r\sin(\theta) &= \frac{p}{1+e\cos(\theta)} \cdot \sin(\theta) \\ \frac{d}{d\theta}(s) = \frac{p \cdot e}{[1+e\cos(\theta)]^2} \cdot \sin^2(\theta) + p\frac{\cos(\theta)}{1+e\cos(\theta)} &= 0 \\ \frac{p \cdot e \cdot \sin^2(\theta)}{[1+e\cos(\theta)]} &= -p \cdot \cos(\theta) \\ p \cdot e\left[\sin^2(\theta)+\cos^2(\theta)\right] &= -p\cos(\theta) \\ \cos(\theta) &= -e \end{aligned} \tag{32}$$

Formula for b:

$$\begin{aligned} b = r \cdot \sin(\theta) &= \frac{p}{1+e \cdot \cos(\theta)} \cdot sin(\theta) \\ fill\,in\,p &= a(1-e^2) \\ r = \frac{a\left(1-e^2\right)}{(1-e^2)} \cdot \sin(\theta) &= a \cdot sin(\theta) \\ \sin^2(\theta) &= 1-\cos^2(\theta) \\ \cos(\theta) &= -e \\ \cos^2(\theta) &= e^2 \\ combining\,gives\,\sin(\theta) &= \sqrt{1-e^2} \\ b &= a \cdot \sqrt{1-e^2} \end{aligned} \tag{33}$$

Substitute into the equation for T:

$$T = \frac{2\pi \cdot a \cdot a \cdot \sqrt{1-e^2}}{\sqrt{a \cdot (1-e^2)\mu}} = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{34}$$

Express a:

$$a = \left[\frac{\mu \cdot T^2}{4 \cdot \pi^2}\right]^{\frac{1}{3}} \tag{35}$$

Find eccentricity according to:

$$
\begin{aligned}
e^2 &= 1 - \frac{rV^2}{\mu}\left[2 - \frac{rV^2}{\mu}\right]\cos^2(\gamma) \\
\mathit{with} \quad \gamma &= \arctan\left(\frac{\dot{r}}{r\dot{\theta}}\right) = -2.1618^\circ
\end{aligned}
\tag{36}
$$

An alternative definition of the eccentricity can be found using the orbital relation:

$$
e = \frac{\tan(\gamma)}{[\sin(\theta) - \tan(\gamma)\cdot\cos(\theta)]} \tag{37}
$$

Knowing that $e < 0.3$, we can plot this to get a first estimation for θ:

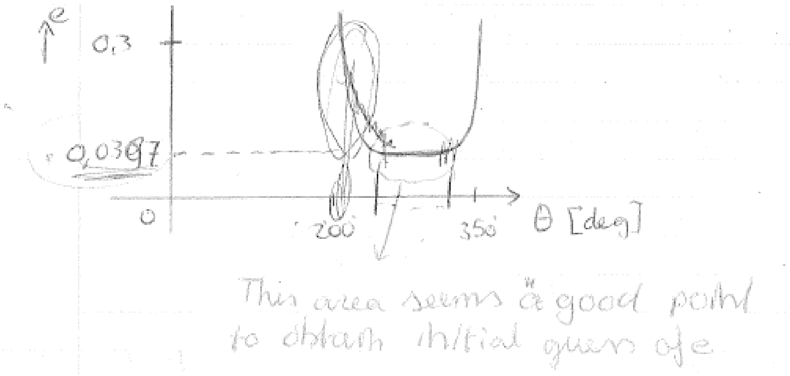

Figure 8: First estimate for θ

3.3 3c

Calculate the values of altitude h of the satellite at t_0 and the height of apogee (h_a) and perigee (h_p) of the orbit

General approach: For a known e and θ, calculate h using:

$$
h = r - R_E = \frac{p}{1 + e\cos(\theta)} - R_E \tag{38}
$$

As we saw earlier, for the perigee we have:

$$
r_p = \frac{p}{1+e} \tag{39}
$$

First, find the flight angle using:

$$
\gamma = \arctan\left(\frac{\dot{r}}{r\dot{\theta}}\right) \tag{40}
$$

Then find V using:

$$
V = \frac{\dot{r}}{\sin(\gamma)} \tag{41}
$$

Then a can be found using:

$$
a = \frac{1}{2}\mu\left[\frac{\mu}{r} - \frac{1}{2}V^2\right]^{-1} \tag{42}
$$

Find p:

$$
p = a(1 - e^2) \tag{43}
$$

So then the perigee altitude can be found from:

$$
h_p = r_p - R_E = \frac{p}{1 + e\cos(\theta)} - R_E \tag{44}
$$

Since p is the same for the whole orbit, we can then also find the apogee altitude from:

$$
h_a = r_a - R_E = \frac{p}{1 - e\cos(\theta)} - R_E \tag{45}
$$

3.4 3d

Calculate the value of the time interval $t_0 - \tau$, where τ is the time of last perigee passage. You may use the transformation relation:

$$\tan\left(\frac{\theta}{2}\right) = \sqrt{\frac{1+e}{1-e}}\tan\left(\frac{E}{2}\right) \tag{46}$$

Further given: $\mu = 398600.4\,km^3/s^2$, $R = 6378.14\,km$.

For a given e and θ, we can rewrite the given equation to express E:

$$E = 2 \cdot \arctan\left[\sqrt{\frac{1-e}{1+e}} \cdot \tan\left(\frac{\theta}{2}\right)\right] \tag{47}$$

Then, using Kepler's equation:

$$E - e \cdot \sin(E) = M \tag{48}$$

But since:

$$M = n\,(t-\tau) = \sqrt{\frac{\mu}{a^3}}\,(t-\tau) \tag{49}$$

So then the interval may be found using:

$$(t_0 - \tau) = \frac{E - e\sin(E)}{\sqrt{\frac{\mu}{a^3}}} \tag{50}$$

4 Question 4

In the field of astrodynamics, there are a number of concepts and definitions to describe the position of points on Earth as well as celestial objects.

4.1 4a

To describe the position of points on the surface of the Earth, the following concepts are used: equatorial plane, meridian, geographic longitude, geocentric latitude, standard ellipsoid, geodetic latitude. Provide an accurate description of these concepts.

The equatorial plate is the plane perpendicular to the rotation axis of the earth, in the middle between the North pole and the South pole:

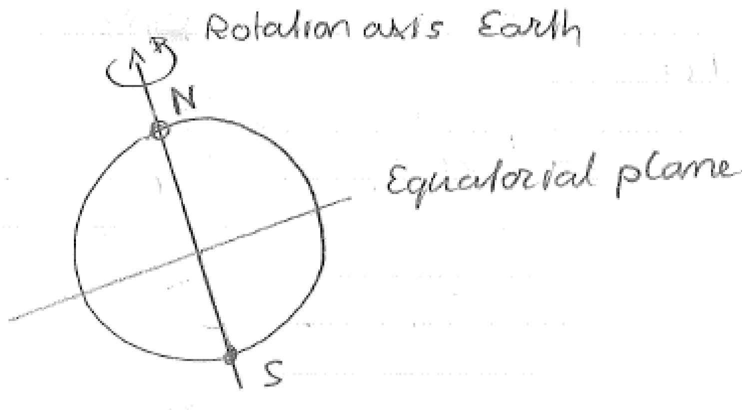

Figure 9: Equatorial plane

The meridian is a circle around the earth that goes through the South pole and North pole.

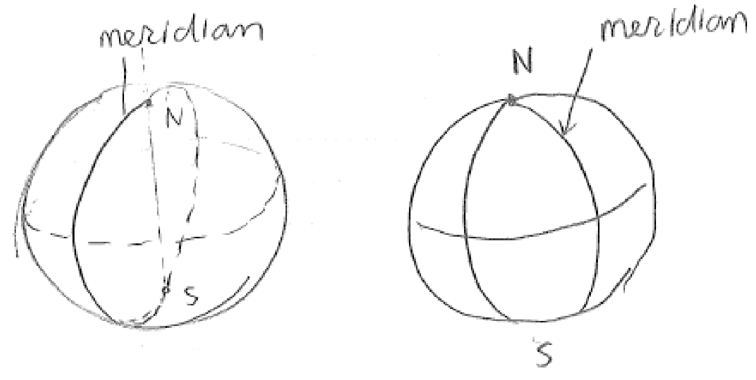

Figure 10: Meridian

Geographic longitude axis is the angle along the equatorial between the Greenwich meridian and the meridian of the observer w.r.t. to the centre of the Earth.

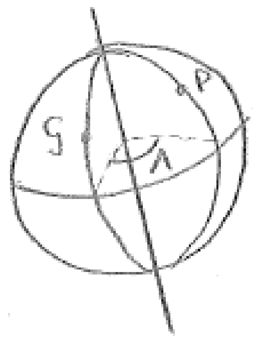

Figure 11: Equatorial plane

The geocentric latitude ϕ is the angle along the meridian of the observer from the equatorial plane to the observer w.r.t. to the centre of the Earth.

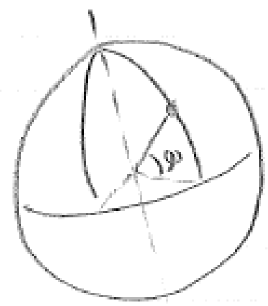

Figure 12: Equatorial plane

The standard ellipsoid is the ellipse that approximates the true shape of the Earth, by taking into account the Earth's flattening.

The geodetic latitude is to the standard ellipsoid what the geocentric latitude is to a circular meridian. It is the angle from the equatorial plane to the observer, along this standard ellipsoid.

4.2 4b

To describe the position of celestial objects, the following concepts are used: celestial sphere, celestial equator, hour circle, declination, right ascending node, ecliptic, obliquity of the ecliptic, vernal equinox. Provide an accurate *description of these concepts.*

The **celestial sphere** is a fictitious sphere on which the sky, as seen from a planet, is projected. It defines a coordinate system XYZ, for which the Z-direction is the celestial North pole, and the X-direction points towards the constellation of Aries.
The **celestial equator** is the intersection of Earth's equatorial plane and the celestial sphere. **Hour circle** are similar to meridians, but roughly divide up the Earth into 24 equal parts. The angle between two hour lines corresponds to one hour of Earth's rotation.
Right ascending node is the horizontal angle between the direction of the vernal equinox and a point on the celestial sphere. This angle is defined parallel to the celestial equator.
Declination is the vertical counterpart to the right ascending node. It is the vertical angle between the celestial equator plane and a point on the celestial sphere.
The **ecliptic** is the path of the Sun over the celestial sphere.
Obliquity of the ecliptic is the angle ϵ, which is the angle between the equatorial plane and the ecliptic plane.
Vernal equinox is the point in Earth's movement around the sun where Earths rotational axis is perpendicular to the Earth-Sun line. This is also the points of intersection of the celestial equator and the ecliptic. The vernal equinox is the moment where it moves from the Southern hemisphere of the Earth to the Northern hemisphere of the Earth (which marks the start of spring on the Northern hemisphere).

4.3 4c

Explain why the vernal equinox is not a fixed point on the celestial sphere, but moves along it. Is the amplitude of luni-solar precession $12°$, $23°$ *or* $34°$? *Is the amplitude of the luni-solar nutation* $9°$, $9'$ *or* $9''$? *Do the luni-solar precession and planetary precession influence the obliquity of the ecliptic?*
The vernal equinox moves constantly along the celestial sphere, because the celestial sphere and the ecliptic are continuously in motion.
The amplitude of luni-solar precession is about $23°$.
The amplitude of luni-solar nutation is about 9".
The luni-solar precession and planetary precession do not influence the obliquity of the ecliptic, but it does "spin" the Earth's equator around the ecliptic North pole.

4.4 4d

To define time, the following concepts are used: sidereal time, solar time, mean solar time, universal time (UT), atomic time (TAI), and universal time coordinated (UTC). Provide an accurate description of these concepts.

From slides:
Sidereal time is time defined by the angular distance covered by the vernal equinox on the celestial sphere after its last crossing of the observer's celestial meridian.
Solar time is time defined by the angular distance covered by the Sun on the celestial sphere after its last crossing of the observer's celestial meridian.
Mean solar time is defined as the hour angle of the mean Sun plus 12 hr.
Universal time is today's realization of a mean solar time, derived from GMST by a conventional relation.
A standardized mean solar time, based on a fictitious, mean Sun that moves at a uniform rate eastward along the celestial equator.
Atomic time is time based on the analysis of about 200 frequency standards (atomic clocks) maintained by several countries to keep a unit of time as close to the ideal SI second as possible (defined in terms of Cesium 133 transitions).
Universal time coordinated is a hybrid standard of time, of which the progression is determined by atomic time (TAI), but leap seconds are introduced, when needed, to keep up with Universal Time (UT1).