Proposed solution for Space Technology I (TTT4234 exam) 1st of December 2016

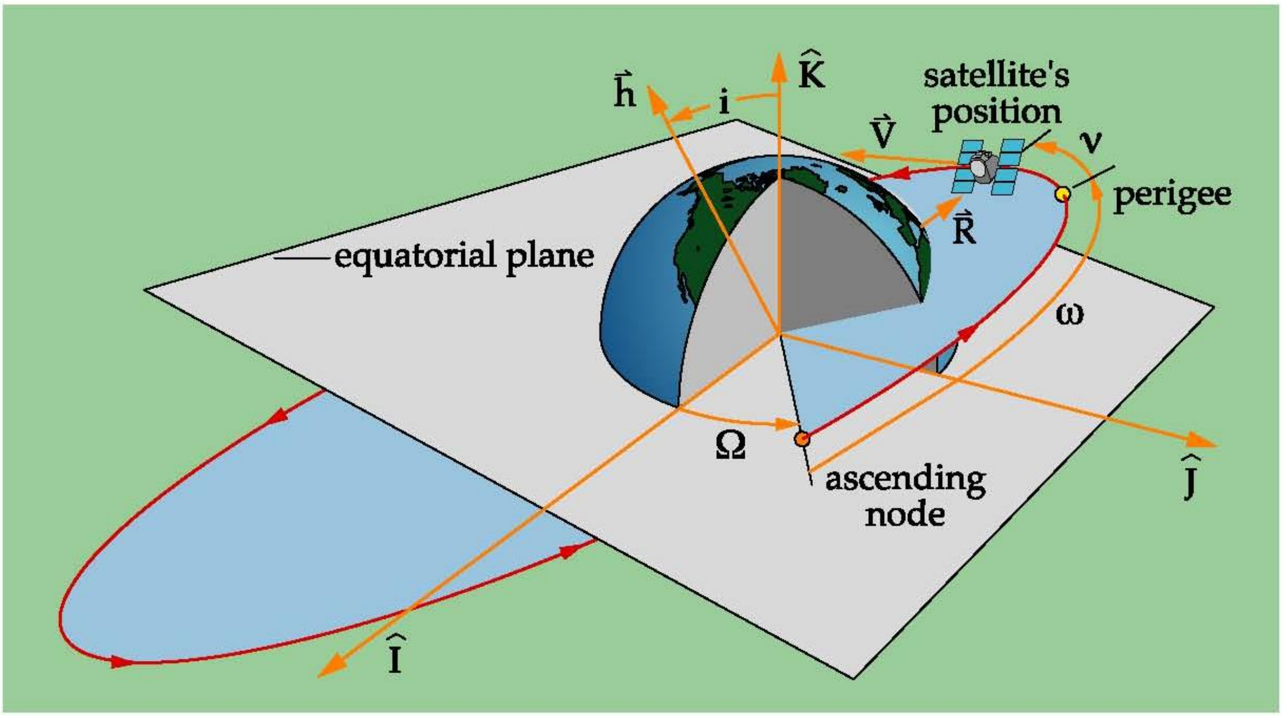
Exercise 1. The Sentinel 1 orbit

On ESA'a home pages, you can read that *"Copernicus is the most ambitious Earth observation programme to date. It will provide accurate, timely and easily accessible information to improve the management of the environment, understand and mitigate the effects of climate change and ensure civil security."*

The Copernicus programme comprises six Sentinel satellites (some of them twin satellites). They are all earth observation satellites that will orbit in LEO, except for Sentinel 4 that is in GEO orbit.

Sentinel 1 observations are radar-based (operating in all weather, day and night) imagery for observing environmental events such as forest fires, landslides and floods. It also provides info and support for assistance and rescue, and long-term missions such as observing melting ice masses of Greenland. The Sentinel 1 satellite is in a sun-synchronous orbit with orbit height 693 km.

a) Describe the 6 classical orbit elements (COE).
Answer:



The reference system is chosen to be I-axis in the equatorial plane pointing from the centre of earth towards vernal equinox (or stellar constellation Aries), K along the rotational axis of earth through the north pole, and J obtained by right-hand vector rule.

a = the semi-major axis
e = the eccentricity
i = the inclination
Ω = the right ascension of the ascending node
ω = the argument of perigee
ν = the true anomaly (time varying)

b) The Sentinel 1 orbit is a sun-synchronous orbit. What are the characteristics of such an orbit? Why do you think this orbit has been chosen for the Sentinel 1 mission?

Answer: A sun-synchronous orbit is a LEO orbit, ideal for earth observation, with an inclination of 98 degrees, so it is almost polar. This is an advantage for observing the ice masses of Greenland. With this inclination, the satellite will have a nodal drift ($d\Omega/dt$) of about 1 degree per day, in order for the satellite's nodal drift to correspond with the solar day of the earth, again in order for the orbit always to have the same orientation with respect to the sun. For such an orbit, it is possible to choose an orbital period so that the satellite always passes over the same area at the same local time every day. In addition, it is possible to choose the right ascension of the ascending node such that the satellite is always in the sun, and hence the solar panels always illuminated (a morning-dawn-orbit).

c) What is the orbital period of the satellite?

Answer: By using Kepler's 3rd law: $T^2 = 4\pi^2 a^3/\mu$, you find that:

$T = \text{Sqrt}(4\,\pi^2 \cdot (693+6370)^3 / 3.986 \cdot 10^5) = 5907\text{s} = 1.64\text{h}$

d) As the satellite uses fuel for orbital corrections, the total mass will decrease as a function of time. How will this influence the orbital height and period?

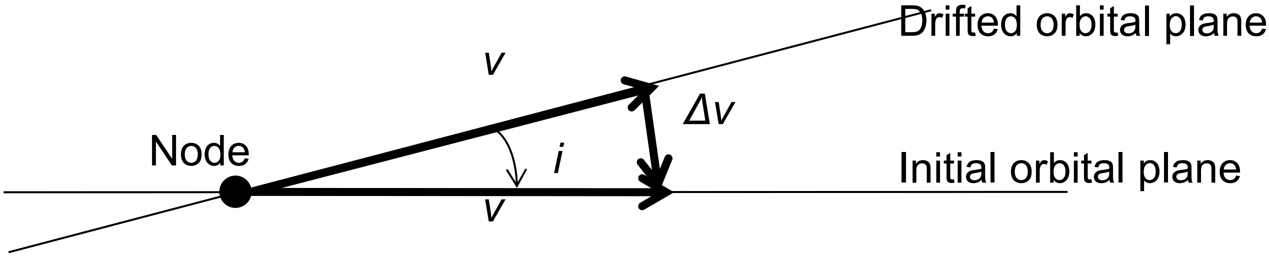
Answer: The orbital height and period are independent of the satellite mass, as can be seen from Kepler's 3rd law. However, other forces such as drag forces and varying gravitational forces may influence these parameters over time.

e) Why do we need to use fuel for orbital correction?

Answer: In a two-body system with a uniform gravitational field from the earth, the mass of the satellite will have no influence on the orbit. But the satellite is influenced by other celestial bodies such as the moon and the sun, and the gravitational field of the earth is not uniform, so the satellite orbit will be perturbed. In addition, come drag forces due to the very thin atmosphere for LEO satellites, sunlight pressure forces, and electromagnetic forces due to the magnetic field of the earth. All these forces will act on the satellite and deorbit the satellite over time. In order to correct the orbit, and the attitude, different measures may be taken, the most common being firing thrusters, using reaction wheels or gyros.

f) Consider a situation where the satellite has drifted out of its nominal orbital inclination by 0.2 degrees. How much fuel is required to correct the orbit? The mass of the satellite and propellant before correction is 2250kg, and the specific impulse of the propellant is 300s.

Answer:



The velocity of the satellite is v = Sqrt(μ/r) = Sqrt $(3.986 \cdot 10^5 / (6370+693)) = 7.51$km/s

Needed correction speed: $\Delta v = v \cdot 2 \cdot \sin(i/2) = 7.51 \cdot 10^3 \cdot 2 \cdot \sin(0.1°) = 26$m/s

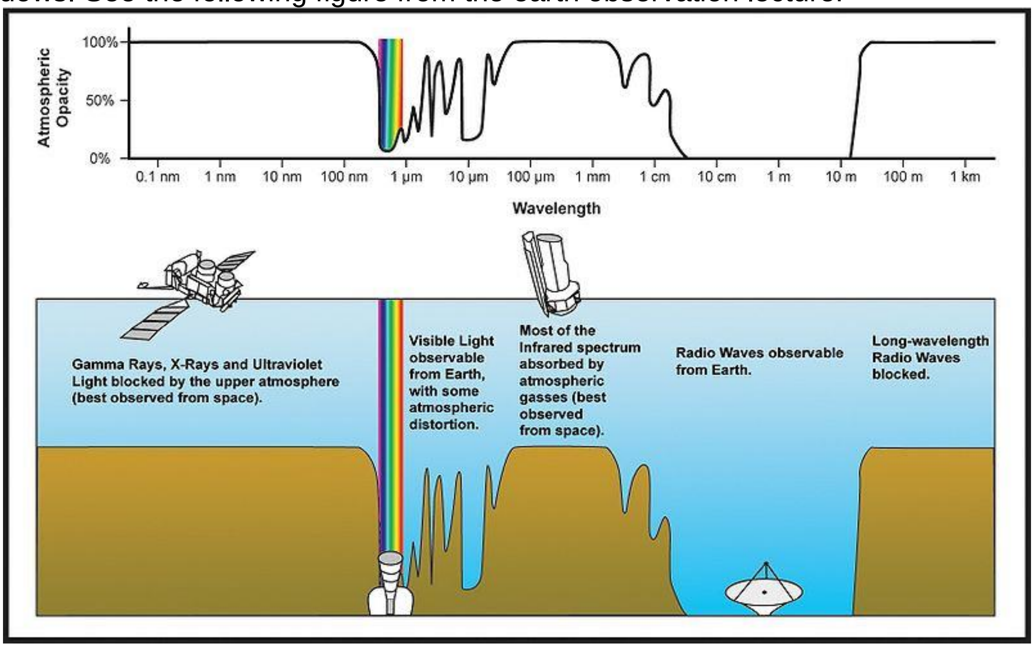
Propellant mass needed for correction:
$m_p = M_i \cdot (1-e^{-\Delta v/(Isp \cdot g0)}) = 2250\ (1-e^{-26/(300 \cdot 9.81)}) = 19.8$ kg.

This is a large amount of fuel, and it shows that corrections “cost” a lot in LEO, since the speed is so high in this orbit.

Exercise 2. The Sentinel 1 earth observation

a) Explain what we call the atmospheric windows.

Answer: radar/radio waves and light (visible and some infrared) are the waves that will pass through the atmosphere with minimum attenuation, these give the two atmospheric windows. See the following figure from the earth observation lecture:



b) The Sentinel 1 earth observation is based on the use of radars. What are the advantages and disadvantages using radar as opposed to optical instruments?

Answer: The resolution of radio wave observation instruments is expressed by R=2.44*λ*h/D. This shows that for the same height above the earth surface, h, and aperture of the instrument, D, small radio wavelengths (light) will give a much better resolution than larger wavelengths (radar). As can be seen from the figure of the atmospheric windows the order of magnitude is as much as 10^6 (1μm as opposed to 1m). However light is difficult to use due to clouds and in night conditions, and is difficult to use in active mode (by illuminating the earth), so radar is preferred as it works by night and the waves penetrate clouds.

c) Explain the principle of Synthetic Aperture Radar (SAR).

Answer: The purpose of the technique is to improve the resolution of radio wave techniques. Light waves give good resolution, but are impractical to use in cloudy conditions and during night. Radio waves do not have this problem, but have a much poorer resolution than light waves for the same h (height above the ground) and D (diameter of the antenna/aperture). The SAR technique will use observations of the same object taken over a certain period of time when flying over, and by combining the information from the observations over time, it may be seen as equivalent to having an aperture the size of the flight track.

d) The data collected on Sentinel 1 has to be transferred to the Earth station when passing over it. The download data rate is 520Mbit/s on X-band (8.3GHz). Which antenna diameter is needed for the Earth station if the required signal to noise ratio is 10dB?

This signal to noise ratio includes a margin for additional losses. The ratio $EIRP/N_0$ = 219 dBHz and the modulation is BPSK. The receiver antenna efficiency is 60%.

Answer:

$L_0=(4\pi d/\lambda)^2 = (4\pi\cdot 693000/(3\cdot 10^8/8.3\cdot 10^9))^2 = 5.8\cdot 10^{16}$ => 168 dB

And BPSK means 1 bit/symbol so B = 520MHz => B = 87.16 dBHz

$S/N = (EIRP/L_0) * (G_r / N_0B) * 1/L_a$ => In dB: $S/N = EIRP/N_0 – L_0 + G_r – B - L_a$

The signal to noise ratio includes a margin for additional losses. In dB: $(S/N)' = S/N + L_a$ = 10dB

In dB: $G_r = (S/N)' – EIRP/N_0 + L_0 + B = 10 - 219 + 168 + 87 =46dB$

$G = \eta \times 4\pi A / \lambda^2$ => In dB: $A = G_r – \eta – (4\pi)_{dB} + \lambda^2 = 46 + 2.2 - 11 -28.8 = 8.4$ dB

$A = \pi (D/2)^2$, $D = 2\cdot Sqrt(A/ \pi) = 2\cdot Sqrt(10^{8.4/10}/ \pi) = 3m$ (2.97m)

Exercise 3. Microgravity

a) Explain why we say that an object is weightless, even though almost the same forces of gravity act upon objects (e.g. a satellite) in orbit around the Earth, as on Earth. Use physical formulas to explain in addition to text, and deduce Kepler's third law.

Answer:
From the microgravity compendium:
"The centripetal force ($F_{cent} = mr\omega^2 = \mu m/r^2$ *with* $\omega=2\pi/T$), necessary to keep the bullet in the circular orbit, is provided by the gravity pull on the bullet. We have earlier discussed the formula (F_{grav} = G $(Mm)/r^2$) for the force of gravity, which is acting on the bullet and attracts it to the earth. When the centripetal force just balances this force of gravity, the bullet will move in a stable circular orbit. *During all the time in orbit, the bullet will be accelerated towards the earth's centre of gravity and will therefore be in free fall (no air friction etc. is considered).*
If we imagine a satellite instead of Newton's bullet we have, in fact, found a way of getting a satellite laboratory that will always be in free fall."

By equaling the force of gravity with the centripetal force, Kepler's third law is obtained:
$T^2 = 4\pi^2 r^3/\mu$

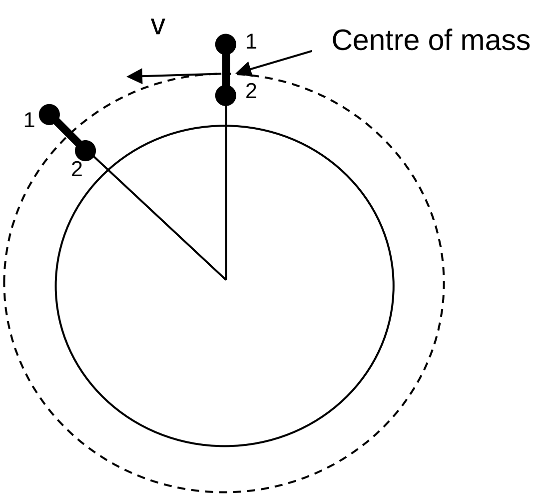
b) With which means can we obtain weightless conditions without going into orbit, e.g. for experiments?

Answer:
The microgravity compendium describes experiments in a drop tower, and in parabolic flights. Astronauts also train for work in weightless conditions in water pools.

c) The other way around, gravitational forces may be simulated in space by different types of constructions. One of them is the tether construction.

Consider a tether construction composed of two identical satellites at a distance of 2d = 5km, and connected via a mechanical and solid rod. The figure below shows the principle of such a system. The center of mass, midway between the two satellites, is in orbit at a height of 200 km above the earth surface.

For satellite number 1, the furthest away from earth, calculate the relative gravitational force as compared to the one experienced by an equivalent mass at rest on the earth surface. Give your interpretation of the result.



Answer:
$F_{cm} = \mu m/r^2 - m\omega^2 r = 0$, so $\mu m/r^2 = m\omega^2 r$

The two satellites must orbit with the same angular speed ω.

So, the force acting on satellite 1 will be: $F_1 = \mu m_1/(r+d)^2 - m_1\omega^2(r+d)$

From the expression of F_{cm}, the angular speed must be $\omega^2 = \mu/r^3$

Then $F_1 = \mu m_1(1/(r+d)^2 - (r+d)/ r^3)$

In order to compare the forces on the satellite to an equivalent force on an object with mass m at rest on the earth's surface $F_e = mg = m\mu/ R_E^2$, we obtain:

$F_1/F_e = R_E^2\ (1/(r+d)^2 - (r+d)/ r^3) = -0.00107$

Interpretation: The centripetal force on satellite 1 is slightly greater than the gravitational force, and without the connection to the other satellite, satellite 1 would have drifted away from its orbit into a larger elliptical orbit.