NTNU – Trondheim
Norwegian University of
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Department of Electronics and Telecommunications

Examination paper for TTT4234 Space Technology I

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Permitted examination support material: Calculator, of a make according to a list approved by NTNU. Printed material: formula sheet attached to the exam.

Other information: Answers should be short and concise.

Language: English

Number of pages: x

Number of pages enclosed: 1

Checked by:

Date Signature

Exercise 1. Norwegian Thor 7 satellite launched into GEO orbit

On the 26th of April 2015, the news on www.spaceflight.com were as follows:

Ariane 5 sends Thor 7 and Sicral 2 satellites into orbit

Posted on April 26, 2015 by Stephen Clark

The Ariane 5 rocket blasts off from Kourou, French Guiana, at 2000 GMT (4 p.m. EDT; 5 p.m. local time). Credit: ESA/CNES/Arianespace – Optique Video du CSG – S. Martin

Blasting into space atop an Ariane 5 launcher, two communications satellites started missions Sunday to beam broadband services to ships, airplanes and offshore oil rigs for a commercial Norwegian operator and relay signals for the Italian and French armed forces.

The dual satellites lifted off at 2000 GMT (4 p.m. EDT) from the Guiana Space Center on the northeastern coast of South America, riding an Ariane 5 rocket across the Atlantic Ocean before deploying into orbit thousands of miles above Earth.

The rocket stayed on the ground 23 extra minutes Sunday to give officials time to resolve a problem with the space center's ground infrastructure.

The Ariane 5's core Vulcain 2 engine and twin solid rocket boosters did most of the heavy lifting, and an upper stage engine guided the Thor 7 and Sicral 2 communications satellites into an egg-shaped geostationary transfer orbit less than a half-hour after launch.

The rocket released Thor 7 first, then re-oriented for separation of a cover to reveal the Sicral 2 spacecraft in the Ariane 5's lower berth.

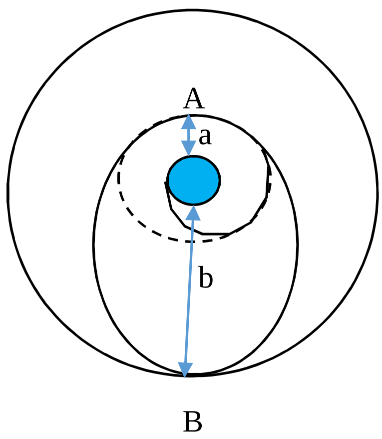
Applause erupted inside the Jupiter launch control center at the French Guiana space base as officials announced the deployment of Sicral 2.

Stephane Israel, Arianespace's chairman and chief executive, confirmed the on-target separation of Thor 7 and Sicral 2.

"Arianespace is delighted to announce that according to our on-board telemetry system Thor 7 and Sicral 2 were separated as planned," Israel said. "Now a long life to Thor 7 and Sicral 2 in orbit."

a) Describe the principle of the use of a Hohmann transfer orbit.
b) For a satellite with an initial circular orbit 200km above earth's surface, the transfer orbit is elliptical with an apogee at GEO, i.e. 35788km above earth's surface. Calculate the changes in speed at the two points where this is necessary in order to place the satellite in a GEO stationary position; at the perigee and at the apogee of the transfer orbit.
c) Thor 7 is now in a GEO orbit at 1 degree west. Describe the Classical Orbit Elements, and the values they take for Thor 7.
d) Why is Thor 7 placed at 1 degree west?

Answers:
a) The goal is to minimize the use of fuel while lifting a spacecraft to a higher orbit.
b) The orbits will be as follows:



$\mu = 3.986 \cdot 10^5$ km^3/s^2
R_E = 6578km

$$v = \sqrt{\mu(2/r - 1/a)}$$

In the first circular orbit r = a = 200+6378 = 6578km
v = $(\mu/r)^{1/2}$ = $(398600/6578)^{1/2}$ = 7.78km/s

At perigee, changing to elliptical orbit, r = 6578km, and a = ½*(2*6378+200+35788) = 24372km.
v = $(\mu(2/r-1/a))^{1/2}$ = $(398600(2/6578-1/24372))^{1/2}$ = 10.239km/s

so Δv = 2.46km/s in A

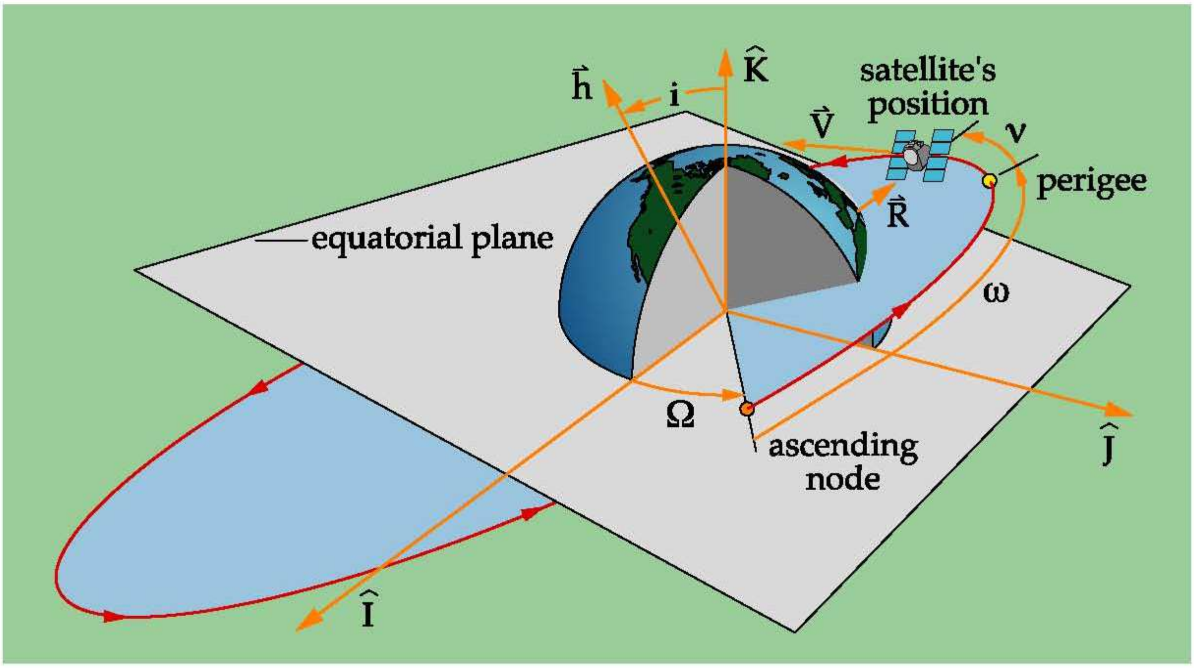
At apogee, changing to circular orbit, r = 6578 + 35788 = 42166km, and this is also r for

the final GEO orbit, and still a = ½*(2*6378+200+35788) = 24372km.
$v = (\mu(2/r-1/a))^{1/2} = (398600(2/42166-1/24372))^{1/2} = 1.597$km/s

In circular GEO: $v = (\mu/r)^{1/2} = (398600/42166)^{1/2} = 3.075$km/s

so Δv = 1.478km/s in B

c)
The 6 classical orbital elements are:
a = the semimajor 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)



The 6 classical orbital elements for Thor 7 will be:

a = r = 42166km
e = 0 (circular orbit)
i = 0 degrees, equatorial plane
Ω = undefined, as no ascending node
ω = undefined as circular orbit and hence no perigee
ν = undefined as circular orbit and hence no perigee

d) Norway has been given the satellite position 1 degree west by the ITU, as this is a position close to the longitude of Norway.

Exercise 2. Thor 7 coverage and link budget

In the article referred to above, we could further read that: *The Thor 7 satellite owned by Norway's Telenor Satellite Broadcasting carries Ku-band and Ka-band telecom payloads to broadcast television across Central and Eastern Europe and provide broadband connectivity to Telenor's clients in the maritime, energy and aeronautical sectors.*

The spacecraft's 25 Ka-band spot beams will offer customers uplink speeds between 2 megabits and 6 megabits per second, supporting applications such as Internet connectivity, remote conferencing, network access, and video streaming.

Thor 7 will also relay meteorological data from Antarctic stations, according to Telenor.

a) Looking at the downlink from Thor 7; Ka-band signals will propagate with a carrier frequency of 20GHz, and Ku-band signals with 12GHz. If the satellite transmitter antennas used are identical, with an antenna diameter of 2m, what will be the difference of the spot beam sizes?
b) What other differences, quantified in dB, will there be between the two signals, as they propagate from Thor 7 to the earth station?
c) A Ka-band link will be used for Antarctica, Why may this be considered a better choice than Ku-band for that link?
d) One of the applications is announced to be "*provide broadband connectivity to Telenor's clients in the maritime, energy and aeronautical sectors."* This means that the uplink capacity from the customers to the satellite has to be shared in what is called multiple access. Describe different types of multiple access techniques.
e) If the choice of access scheme is TDMA, and the bandwidth is $B=1/T=4MHz$, and each user shall be given 320kbit/s with time slots 40ms long and uncoded QPSK modulation, how many simultaneous users may be offered access?

Answer:

a) The antenna beamwidth is $\theta = k\lambda/D$ where k is a constant that takes a value of ~70 for parabolic antennas. $\lambda = c/f$, and D is the diameter of the antenna.
For 20GHz, $\theta = 70*3.10^8/(20.10^9)/2 = 0.52$ degrees, while for 12Gz, $\theta = 70*3.10^8/(12.10^9)/2 = 0.88$ degrees. The spot is much larger for Ku-band.

b) Looking at the link budget, the free space loss $L_0 = (4\pi d/\lambda)^2 = (4\pi df/c)^2$, here d is the distance from the transmitter to the receiver, we see that the signal loss will be higher with higher frequencies, in this case $20\log(20/12) = 4.4dB$ more.

c) Still, even though we have a bigger free space loss than for Ku-band, Ka-band may be preferred for the following reasons:
   - We do not need a big spot beam, as we are just sending to one/very few antennas in a very restricted area
   - The additional losses La are small for Ka-band in Antarctica, as the atmosphere is very dry over the poles
   - The antenna gains increase with frequency as $G=\eta 4\pi A/\lambda^2$, by the same amount as the free space loss, 4.4dB as we go from 12GHz to 20GHz.

d) As a minimum: FDMA, TDMA and CDMA with description……..

e) In a 4MHz bandwidth with QPSK, the bit rate will be 8Mbit/s. A slot of length 40ms will contain 8Mbit/s*40ms = 320kbits. Hence every user needs one slot per second, and the number of users will be 1s/40ms = 1/0.04=25 users simultaneously.

Exercise 3. Attitude control and satellite power systems

The picture below shows an artistic view of Thor 7 from the abovementioned article.

a) Attitude and orbit control are important for Thor 7. Explain why, and what mechanisms that may be used to keep the satellite in position.
b) How much fuel will be needed for thrusters to correct the orbit of Thor 7, supposing the satellite has drifted into an orbit with 0.1 degree inclination, the mass of Thor 7 being 2500kg before the correction, and using a fuel with specific impulse I_{sp}=300s.
c) For some days around the equinoxes, a GEO satellite will enter into eclipse. What will happened then, and what measures are taken to keep the satellite working during those periods.
d) The solar cell degradation factor is $F_s = 0.7 + 0.3\ e^{-\text{nb. of days}/1000}$.At the beginning of life, the solar cells of Thor 7 are delivering 2.5kW, and the minimum needed to keep the satellite running is 1.76kW. What is the degradation factor, and for how many years will the solar panels keep Thor 7 alive?
e) Comment on the lifetime of the satellite considering b) and d), knowing that the Dry mass of the satellite is 1600kg, and that the only correction is the inclination correction twenty times a year.

Answers:

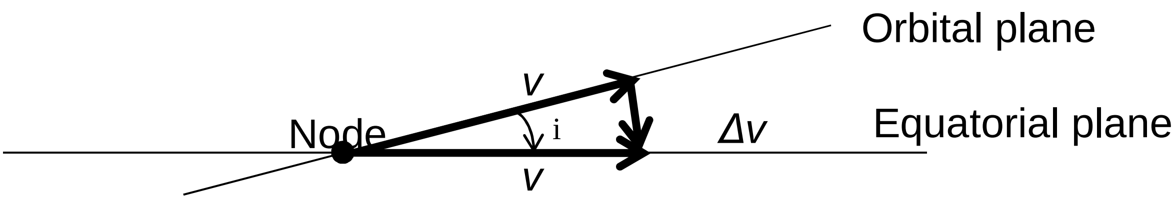
a) It is important for pointing antennas and solar panels correctly. And if a GEO stationary satellite starts drifting, it will no longer be stationary.

b) The rocket equation, $\Delta v = v_e \cdot \ln (M_i/M_f)$, can be rearranged to

$$\Delta M = M_i(1-e^{-\Delta v/g_0 I_{sp}}),$$

where $\Delta M = M_i - M_f$ is the amount of fuel/propellant used for the orbital correction, and M_i is the initial mass for the entire satellite construction before correction (i.e. structure, payload and fuel). Δv is the velocity change necessary to perform the orbital correction, g_0 is the gravitational acceleration, and I_{sp} is the specific impulse of the propellant used, giving the efficiency of the propellant. I_{sp} = 300s, and we always use $g_0 = 9.81 m/s^2$ in this equation.

The figure below shows the correction to perform:



We know from 1b) that the velocity in GEO orbit is 3.075km/s. The necessary velocity change will be: $\Delta v = v\cdot 2\cdot \sin(i/2) = 3.075\cdot 10^3\cdot 2\cdot \sin(0.05°) = 5.4 m/s$.

i is so small that using both $\Delta v = v\cdot \sin(i)$ and even $\Delta v = v\cdot i$ (i in radians) is ok.

Then: $\Delta m/m_i = (1-e^{-\Delta v/g_0 I_{sp}}) \approx 1-e^{-5.4/(9{,}81\cdot 300)} = 0.0018$. I.e. the mass of the satellite has been reduced by approximately 1.8‰ by this correction.

This gives Δm=4.55kg of fuel that has to be used to get the satellite back into the correct orbit.

c) The satellite will go into eclipse, and needs batteries to power the satellite while in eclipse.

d) The degradation factor is Fs= 1.76kW/2.5kW = 0.704. The time will be t=1000*ln(0.3/(0.704-0.7))=4317 days => 11.82 years.

e) The fuel mass is then 2500kg-1600kg = 900kg. With corrections 20 times pr. year, approximately 20*4.55kg will be needed (actually a bit less as the mass of the satellite reduces with the fuel mass uses every time the engines are fired, and the last time only 0.0018*1600= 2.88kg is needed). But this gives approximately 10-15 years lifetime, and the solar panels about 12 years, so they are evenly dimensioned.

Exercise 4. Launch description

Choose one of the two topics below.

a) Explain the rocket equation, and with reference to the first cosmic speed, why we need several stages on a launcher today, to place a satellite into orbit.
b) Discuss different types of propellants and their advantages and drawbacks.

Thor 7 lifting off. From www.spaceflight.com; **Credit: ESA/CNES/Arianespace – Optique Video du CSG – S. Martin**