EXAM AE1-801 SPACE ENGINEERING & TECHNOLOGY I

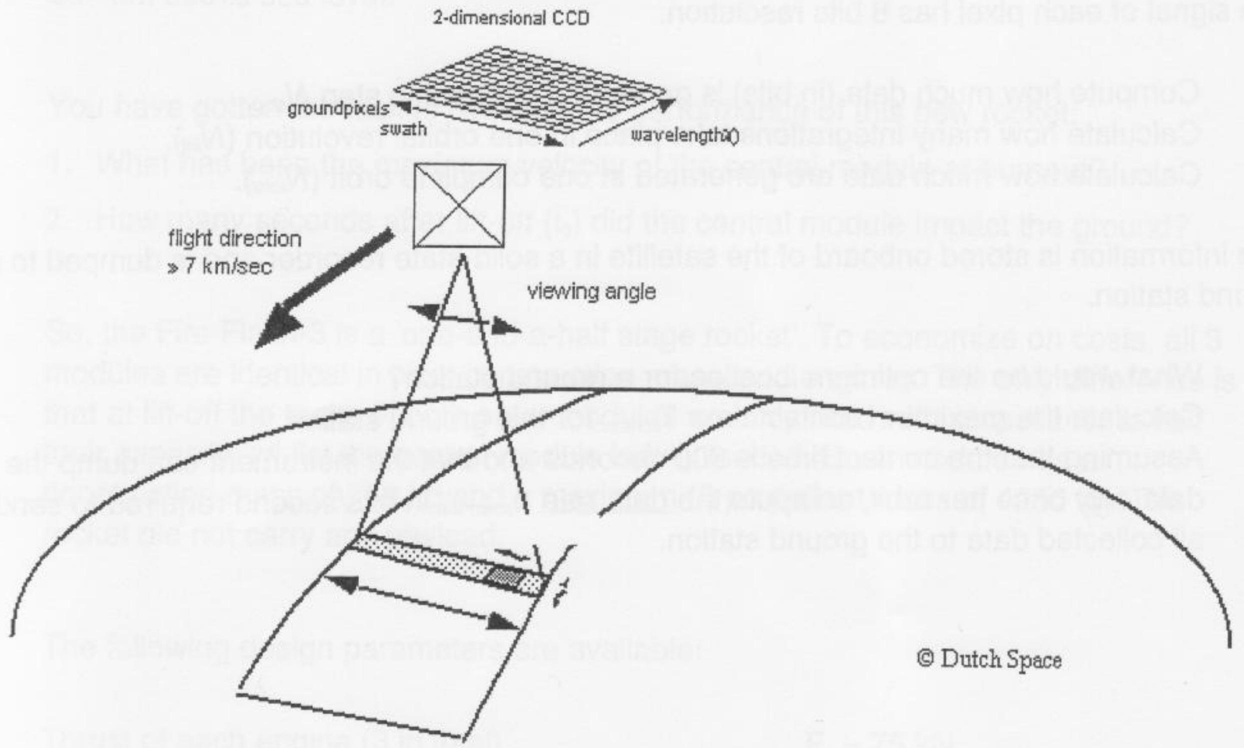
26 JUNE 2006

This problem is related to the part *Space Missions & Systems* of the course *ae1-801*.

Problem 1 Earth observation instrument (25 points)

An Earth observation instrument flies onboard a satellite in a circular polar orbit and measures reflected solar radiation form the Earth's atmosphere in the ultra-violet and visible spectrum. The orbital altitude h is 570 km, the orbital period T_{orb} is 96 minutes and the Earth radius R_E is 6375 km.

a. Calculate the orbital velocity V_{orb}



The instrument is looking down to Earth, so viewing in nadir direction. Its viewing angle in a direction normal to the orbital plane (cross-track) is 20 degrees, in the orbital plane (along-track) 1 degree.

b. Compute the size (L_{ct} and L_{at}) of the instantaneous image on the ground in kilometers.

The cross-track direction of the image is imaged on 64 pixel elements of a CCD.

c. Calculate the spatial resolution RE_{ct} in km per pixel in the cross-track direction.

It is preferred to have the spatial resolution in along-track direction the same size as in cross-track direction. In along-track direction the spatial resolution is determined by the integration time of the detector.

d. Calculate the along-track velocity on the ground V_{ground}

e. Compute the required integration time t_{int} to achieve equal cross-track and along-track spatial resolution.

For each ground pixel the incoming radiation is analyzed in a spectral image, that is image on 250 pixel elements.

f. Calculate the total number of detector pixels N_{det}.

The instrument measures the spectral range between 250 and 500 nanometer.

g. Calculate the spectral resolution RE_{sp} in nanometer/pixel.

The signal of each pixel has 8 bits resolution.

h. Compute how much data (in bits) is generated integration step N_{step}.

i. Calculate how many integrations take place in one orbital revolution (N_{int}).

j. Calculate how much data are generated in one complete orbit (N_{total}).

This information is stored onboard of the satellite in a solid-state recorder and is dumped to a ground station.

k. What would be the optimum location for a ground station?

l. Calculate the maximum contact time $T_{contact}$ for this ground station.

m. Assuming that the contact time is 600 seconds and that the instrument can dump the data only once per orbit, compute the data rate $n_{down\ link}$ in bits/second required to send all collected data to the ground station.

Problem 2 (35 points)

This problem (2) is related to the part *Rocket Motion* of the course *ae1-801*.

Following a new trend in the space launcher business, a new rocket (Fire Flash-3) has been developed based on the concept of parallel stages. It consists of 3 identical modules, which are mounted side-by-side. At launch all engines are ignited simultaneously. Such a configuration is known as a 'one-and-a-half stage rocket'. Each module of the Fire Flash-3 is powered by a single (identical) rocket engine. The only difference is the amount of propellants carried by the 3 modules. The central module is fully loaded at launch time, while the other 2 modules are only filled to half their capacity. After burnout, the 2 outer modules are jettisoned, while the central module continues to function until its propellants are also depleted. During its first test mission, the rocket performed nominally, flying a vertical trajectory. At the moment of burnout of the central module a tracking station measured an altitude of 307 km above sea level.

You have gotten the task to evaluate the performance of this new rocket:

1. What has been the maximum velocity of the central module at burnout?
2. How many seconds after lift-off (t_0) did the central module impact the ground?

So, the Fire Flash-3 is a 'one-and-a-half stage rocket'. To economize on costs, all 3 modules are identical in size, construction mass, and engines. The only difference is that at lift-off the tanks of both outer modules are only filled with propellants to half their capacity, whilst the central module is fully loaded. Each module has a construction mass of 750 kg and a maximum (!) propellant mass of 4250 kg. The rocket did not carry any payload.

The following design parameters are available:

Thrust of each engine (3 in total)	$F = 75$ kN
Specific impulse of the engines	$I_{sp} = 300$ s
Gravitational acceleration	$g_0 = 9.81$ m/s2

For simplicity, you may assume that the rocket moves perfectly vertical throughout the flight and the flight takes place in a homogeneous gravity field ($g = g_0$ = constant) in vacuum.

a. Compute the total mass of the rocket (2 pts)
b. Compute the burn time of the outer modules until their propellants are depleted (2 pts)
c. Compute the remaining burn time of the central module until burnout (2 pts)
d. List the necessary expression for the consecutive calculation steps (N.B. 2) that are necessary to compute the velocity of the central module at burnout (6 pts)

e. Follow the calculations steps you have listed under d) and compute the velocity of the central module at burnout. (13 pts)

f. List the consecutive calculation steps that are necessary to compute the total duration of the test flight after ignition of the engines (t_0) until the second stage crashes on the ground. (5 pts)

g. Follow the calculations steps you have listed under f) and calculate the total flight duration from the moment of ignition of the engines until the central module crashes on the ground. (5 pts). If you did not succeed in calculating the velocity under question e), please assume $Ve_2 = 4965$ m/s.

N.B. Derivations of formulae like Tsiolkowski's equation are not requested, but may be helpful to find the correct expressions.

For problems 3 and 4 the following equations may be used without derivation:

$$r = \frac{a(1-e^2)}{1+e\cos\theta} = a(1-e\cos E) \tag{1}$$

$$M = E - e\sin E \tag{2}$$

$$\frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a} \tag{3}$$

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{4}$$

$$\Delta\omega = \frac{3}{2}\pi J_2 \left(\frac{R_e}{p}\right)^2 (5\cos^2 i - 1) \text{ (per orbital revolution)} \tag{5}$$

$$\Delta\Omega = -3\pi J_2 \left(\frac{R_e}{p}\right)^2 \cos i \text{ (per orbital revolution)} \tag{6}$$

Furthermore, the following parameters are given:

- Mean radius of the Earth: $R_e = 6371$ km
- Mean radius of Pluto: $R_{Pluto} = 0.18\ R_e$
- Gravity parameter of the Earth: $\mu_e = 398600$ km^3/s^2
- Gravity parameter of Pluto: $\mu_{Pluto} = 2.13 \times 10^{-3}\ \mu_e$
- Gravity parameter of the Sun: $\mu_{Sun} = 1.3271 \times 10^{11}$ km^3/s^2
- Distance Earth-Sun : $r_e = 1$ AU
- Distance Pluto-Sun: $r_{Pluto} = 39.44$ AU
- 1 AU = 150×10^6 km
- Second zonal harmonic coefficient: $J_2 = 1.082627 \times 10^{-3}$

Grading:
- Problem 3: 25 points
- problem 4: 15 points

Problem 3. Mission to Pluto

Consider a satellite mission from the Earth to Pluto. The interplanetary flight from the Earth to Pluto is conducted by means of a Hohmann transfer orbit.

a. What is the average mass density ratio of Pluto compared to Earth?

b. Derive the orbital revolution periods (in years) of the Earth and Pluto around the Sun.

c. What is the apocenter location and what is the pericenter location of the Hohmann transfer orbit?

d. Compute the travel time from the Earth to Pluto.

e. Compute the synodic period for the Pluto-Earth-Sun constellation.

f. Compute the minimum lay-over time (or the time the satellite has to wait while circling around Pluto) in case the satellite has to travel back to the Earth by again a Hohmann transfer. What is the total minimum mission duration?

Problem 4. Perturbing forces

Perturbing forces, i.e. forces that deviate from the central gravity field term, cause a satellite's orbit around the Earth to deviate from a perfect Keplerian orbit. These perturbing forces can sometimes be advantageous for certain satellite orbits around the Earth.

Sun-synchronous satellite orbits:

a. What is a sun-synchronous orbit?

b. Give at least three possible advantages of flying a sun-synchronous orbit (consider especially so-called "dawn-dusk" orbits with a local time of 6 AM or 6 PM at equator crossings).

c. Compute the inclination of a sun-synchronous circular orbit at 250 km altitude above the Earth.

d. Does the inclination of a circular sun-synchronous orbit decrease or increase with higher altitudes?

EXAM AE1-801, SMS; TEST

SPACE ENGINEERING & TECHNOLOGY I

PART SPACE MISSIONS & SYSTEMS

3 NOVEMBER 2005

09:00-11:00

This exam consists of 3 problems with several items. Start each problem on a fresh sheet of paper. Remember to clearly indicate your name and student number on each sheet. Show in your answers also the formulae that you are using. Insert the numerical values you use stepwise.

You are supposed to make the exam individually and you may not use books, lecture notes or your own notes with this exam.

PROBLEM 1 (20 points; 25 minutes)

A satellite may be broken down in a payload and the remainder of the satellite.

1a Give the function and the definition of "payload" and its function according to the convention used in "Space Mission Analysis & Design" [Larson].

1b How is the remaining part of the satellite called? What is its function and definition?

The remaining part of the satellite is broken down into seven subsystems according to Larson.

1c List the seven subsystems.

1d Give the principal functions of each of the subsystems.

TENTAMEN AE1-801, SMS; TEST

SPACE ENGINEERING & TECHNOLOGY I

DEEL SPACE MISSIONS & SYSTEMS

3 NOVEMBER 2005
09:00-11:00

Dit tentamen bestaat uit 3 vraagstukken met onderdelen voor een totaal van 100 punten. Tijden vermeld zijn indicatief. Begin elk vraagstuk op een nieuw blad. Vermeld duidelijk uw naam en studienummer op elk blad. Laat bij de beantwoording van de vragen ook eventuele gebruikte formules zien. Vul de getalswaarden, die u gebruikt, stapsgewijs in.

U wordt verondersteld dit tentamen individueel te maken en u mag geen boeken, dictaten of aantekeningen bij het tentamen gebruiken.

VRAAGSTUK 1 (20 punten; 25 minuten)

Een satellite kan onderverdeeld worden in een nuttige last en een resterend deel van de satellite.

1a Geef de funktie en de definitie van "nuttige last" volgens de conventie gebruikt in "Space Mission Analysis & Design" [Larson].

1b Hoe wordt het resterend deel van de satellite genoemd? Wat is de functie en de definitie daarvan?

Het resterend deel van de satellite wordt onderverdeeld in zeven subsystemen volgens Larson.

1c Noem de zeven subsystemen.

1d Geef de hoofdfuncties van jeder van de zeven subsystemen.

PROBLEM 2 (45 points; 55 minutes)

You are asked to perform a feasibility analysis for a satellite constellation for mobile telephone services.

2a Assuming that

- a mobile telephone user is willing to pay a world-wide charge of 0.15 US$ per minute for a 99% availability of the service
- the user makes 100 such one minute calls per month
- a Mobile Satellite Services (MSS) constellation with 6 years lifetime costs 4 G$
- operations of the system cost 200 M$ per year
- billing services cost 100 $ per user per year (expenses of the mobile telephone operator)
- investors want to recover their money with 20% annual yield

Calculate income, expenses and investor's profit as a function of the number of customers N. How many customers does the constellation operator need?

2b Do you think that is economically feasible? Motivate your answer.

2c Assuming that

- the constellation has 66 satellites
- all calls take place during day time (8 hours)
- 25 million users are uniformly distributed over the Earth's surface
- all mobile calls are to a fixed telephone number
- a peak load of two times the average load (think about the 99% availability)

How many telephone lines should be available per satellite? Hint: calculate first the total average number of telephone calls per day of 8 hours.

2d The MSS Iridium constellation has the following characteristics:

- World-wide system for mobile communication
- 2800 two-way channels for speech per satellite
- 66 satellites distributed over 6 orbit planes (constellation)
- Cost (all system): 4 G$
- Circular sun-synchronous orbit: 785 km
- Lifetime: 6 year
- Inter-satellite links

Do you think the Iridium constellation is a technically feasible solution for your problem? If not, indicate why. Could you think of measures to improve the situation? Motivate your answer.

VRAAGSTUK 2 (45 punten; 55 minuten)

U wordt gevraagd een haalbaarheidsanalyse uit te voeren voor een satellietconstellatie voor mobiele telefonie.

2a We nemen aan dat

- een mobiele telefoon gebruiker bereid is 0,15 US$ per minuut te betalen voor wereldwijde dekking bij een systeem beschikbaarheid van 99%
- die gebruiker 100 van die gesprekken van één minuut per maand voert
- een Mobile Satellite Services (MSS) constellatie met 6 jaar levensduur 4 G$ kost
- de operaties van het systeem 200 M$ per jaar kosten
- administratiekosten 100 $ per gebruiker per jaar bedragen (ten laste van de exploitant)
- investeerders hun geld willen terug zien met 20% jaarlijks rendement

Bereken inkomsten, uitgaven en de winst van de investeerder als een functie van het aantal klanten N. Hoe veel klanten heeft de operator van de constellatie nodig?

2b Denkt u dat dit economisch haalbaar is? Motiveer uw antwoord.

2c Neem nu aan dat

- de constellatie 66 satellieten heeft
- alle gesprekken overdag plaats vinden (in 8 uur)
- er 25 millioen gebruikers uniform over het oppervlak van de aarde verspreid zijn
- alle mobiele gesprekken naar een vast telefoon nummer gaan (het normale netwerk)
- de piekbelasting twee maal de gemiddelde belasting is (denk aan de 99% beschikbaarheid)

Hoe veel telefoon lijnen moeten dan per satelliet beschikbaar zijn?

Aanwijzing: bereken eerst het totale gemiddelde aantal telefoon gesprekken per dag van 8 uur.

2d De MSS Iridium constellatie heeft de volgende karakteristieken:

- wereldwijd systeem voor mobiele communicatie
- 2800 twee-weg kanalen voor spraak per satelliet
- 66 satellieten verdeeld of zes baanvlakken (constellatie)
- kosten van het hele systeem: 4 G$
- circulaire zon-synchrone baan: 785 km
- levensduur: 6 jaar
- verbindingen tussen de satellieten onderling

Denkt u dat de Iridium constellatie een technisch haalbare oplossing is voor uw probleem? Indien dit niet het geval is, geef aan waarom. Kunt u maatregelen bedenken om de situatie te verbeteren? Motiveer uw antwoord.

PROBLEM 3 (35 points; 40 minutes)

A satellite with a dry mass of 2000 kg (that is excluding propellants, but including tanks and motor) has to be transferred from a circular earth orbit with an altitude of 200 km to a geo-stationary orbit with an altitude of 35786 km. The assignment is to determine the characteristics of the propulsion system to enable this. The Earth radius R_E equals 6367 km.

3a Compute the orbital speed V_{200} in that low parking orbit, taking into account an orbital period of 88.49 minutes.

3b Give the definition of a geo-stationary orbit.

3c The orbital period in the geo-stationary orbit is 23.945 hours. Compute the orbital velocity V_{GEO} in the geo-stationary orbit.

3d A velocity increment of 3950 m/s is required to get from the parking orbit to the geo-stationary orbit. The rocket motor of the satellite's propulsion system has an exhaust velocity of 3000 m/s. Calculate with Tsiolkowski the mass ratio M_0/M_e of the satellite in the parking orbit (M_0 is the wet satellite mass, so including the propellants). Compute also M_p/M_0 (the fraction of the total mass that is used for propellants, where the propellant mass $M_p = M_0 - M_e$).

3e Compute the kinetic energy E_{LEO} in the parking orbit and E_{GEO} in the geo-stationary orbit. Does the kinetic energy increase or decrease?

3f Estimate the energy added to the satellite by the rocket motor. You can do this by calculating the kinetic energy the satellite would have at the end of the burning time of the rocket motor in a space with zero gravity. Assume that the mass at the end of the burning time equals the end mass of the satellite.

3g How do you explain the difference between the kinetic energy in the parking orbit plus the added kinetic energy and the kinetic energy in the geo-stationary orbit?

VRAAGSTUK 3 (35 punten; 40 minuten)

Een satelliet met een droge massa van 2000 kg (dat is exclusief stuwstoffen maar inclusief tanks en motor) moet van een circulaire aardbaan met een hoogte h_E van 200 km naar een geostationaire baan met een hoogte van 35786 km gebracht worden. De opdracht is om de karakteristieken te bepalen van het voortstuwingssysteem dat dit mogelijk maakt. De aardstraal R_E is gelijk aan 6367 km.

3a Bereken de baansnelheid V_{200} in die lage parkeerbaan, rekening houdend met een omlooptijd van 88.49 minuten.

3b Geef de definitie van een geostationaire baan.

3c De omlooptijd in de geostationaire baan is 23.945 uur. Bereken de baansnelheid V_{GEO} in de geostationaire baan.

3d Om van de parkeerbaan in de geostationaire baan te komen is een snelheidstoename nodig van 3950 m/s. Het raketmotor van het voortstuwingssysteem van de satelliet heeft een uitstroomsnelheid van 3000 m/s. Bereken met Tsiolkowski de massa verhouding M_0/M_e van de satelliet in de parkeerbaan (M_0 is de natte satellietmassa, dus inclusief stuwstoffen). Bereken ook M_p/M_0 (de fractie van de totale massa die gebruikt wordt voor stuwstoffen, waarbij de stuwstofmassa $M_p = M_0 - M_e$).

3e Bereken de kinetische energie van de satelliet in de parkeerbaan en in de geostationaire baan. Is er sprake van een toename of een afname van de kinetische energie?

3f Maak een inschatting van de energie die aan de satelliet is toegevoegd door de raketmotor. U kunt dit doen door de kinetische energie uit te rekenen die de satelliet in een gravitatievrije ruimte zou hebben aan het eind van de brandduur van de raketmotor. Neem aan dat de massa aan het eind van de brandduur gelijk is aan de eindmassa van de satelliet.

3g Hoe verklaart u het verschil tussen de kinetische energie in de parkeerbaan plus de toegevoegde kinetische energie en de kinetische energie in de geostationaire baan?

TENTAMEN AE1-801, SPACE ENGINEERING & TECHNOLOGY I
29 augustus 2005
09:00 – 12:00 uur

Dit tentamen bestaat uit 5 vraagstukken met onderdelen. Begin elk vraagstuk op een nieuw blad. Vermeld duidelijk uw naam en studienummer op elk blad. Laat bij de beantwoording van de vragen ook eventuele gebruikte formules zien. Vul de getalswaarden, die u gebruikt, stapsgewijs in.

Vraagstuk 1 (18 punten; 30 minuten)

Deze vraag (1) heeft betrekking op het deel *Space Missions & Systems* van het college *ae1-801*.

We willen vanuit de ruimte het volledige stralingsspectrum van hemellichamen observeren voor lange perioden. Het lijkt aantrekkelijk om ver van de aarde weg te gaan, omdat

- De aarde zelf een bron van straling is (warmte en gereflecteerd zonlicht),
- Dichtbij de aarde de tijd, gedurende welke een hemellichaam (een punt in de inertiële ruimte) ononderbroken geobserveerd kan worden, beperkt is (de aarde passert de satellite – object lijn),
- We lange contacttijden hebben met het grondstation, en we dus minder data opslag en minder geavanceerde autonomie aan boord nodig hebben en kosmische gebeurtenissen real time kunnen zien.

Er zijn echter ook nadelen.

Vragen

Noem de nadelen van dit concept vanuit de volgende gezichtspunten:

1a Ruimte omgeving

1b Lanceer capaciteit

1c Communicatie

1d Richtnauwkeurigheid

1e Elektrisch vermogen

1f Baan- en standregeling

Wees specifiek in uw antwoord; geef een rationale voor ieder nadeel dat u kunt identificeren.

Vraagstuk 2 (7 punten; 15 minuten)

Deze vraag (2) heeft betrekking op het deel *Space Missions & Systems* van het college *ae1-801*.

Een robot arm van 10 m lengte moet een nuttige last van 6000 kg massa verplaatsen. De actuator aan de basis van de arm oefent een koppel van 300 Nm uit.

2a In hoeveel tijd heeft de robot arm de nuttige last over 180 graden verplaatst?

2b Om elektrisch vermogen te besparen bestaat de actuator uit een kleine motor met een reductie overbrenging (overbrengingsverhouding 1:400). Hoe groot is het motor koppel?

Probleem 3 (40 punten)

Probleem 3 is gerelateerd aan onderdeel *Rocket Motion* van *ae1-801.*

De nieuw ontwikkelde twee-trapsraket Vuurflits-2 heeft zijn tweede testvlucht ondergaan. De eerste trap wordt aangedreven door twee identieke motoren en de tweede trap door een enkele motor van exact hetzelfde type. Een probleem in de eerste trap leidde ertoe dat een van beide motoren niet ontbrandde. Dientengevolge vertrok de raket niet onmiddelijk van het lanceerplatform, maar pas nadat het gewicht voldoende was afgenomen tot het moment dat dit in balans was met de stuwkracht van de overblijvende motor. Deze bleef functioneren totdat alle stuwstoffen waren opgebruikt. De tweede trap ontbrandde onmiddelijk na het doven van de eerste trap. Deze trap functioneerde nominaal. Het volgstation mat dat de tweede trap een hoogte van 142 km boven zeeniveau had bereikt op het moment van uitbranden.

Je hebt de opdracht om de prestatie en de gevolgen van het afslaan van een van de motoren van de eerste trap te evalueren:

1. Wat is de maximale snelheid geweest op het moment dat de tweede trap uitdoofde?
2. Hoeveel seconden na ontsteken van de eerste trap(t_0) sloeg de tweede trap in op de grond?

De Vuurflits-2 is een 2-trapsraket. Om op de kosten te besparen zijn beide trapen identiek wat betreft absolute massa en stuwstof massa. Het enige verschil is dat de eerste trap twee motoren heeft en de tweede trap slechts een. Beide trappen hebben een constructiemassa van 750 kg en een brandstofmassa van 4250 kg. Bij deze testvlucht werd een nuttige lading van 500 kg vervoerd.

De volgende ontwerpparameters zijn beschikbaar:

Stuwkracht van elke motor (3 in totaal)	$F = 80$ kN
Specifieke impuls van de motoren	$I_{sp} = 300$ s
Gravitatieversnelling	$g_0 = 9.81$ m/s2

Ter vereenvoudiging mag je aannemen dat de raket perfect vertikaal beweegt gedurende de gehele vlucht, en de vlucht plaatsvindt in een homogeen zwaartekrachtveld ($g = g_0 =$ constant) in vacuüm.

a) Bereken de totale massa van de raket (2 punten)
b) Bereken de werkelijke brandtijd van beide trappen (2 punten)
c) Bereken het tijdstip waarop de raket daadwerkelijk vertrekt van het lanceerplatform (4 punten)
d) Analyseer het probleem en maak een lijst met alle opeenvolgende rekenstappen (N.B 3) die nodig zijn om de snelheid te berekenen van de tweede trap op het moment dat deze dooft. (8 punten)
e) Volg de rekenstappen die je onder d) hebt aangegeven en bereken de snelheid van de tweede trap op het moment dat deze dooft. (14 punten)
f) Maak een lijst met alle opeenvolgende rekenstappen die nodig zijn om de totale duur van de testvlucht te berekenen vanaf het ontsteken van de eerst trap (t_0), tot het inslaan van de tweede trap op de grond. (5 punten)
g) Volg de rekenstappen die je onder f) hebt aangegeven en bereken de totale duur van de testvlucht, gerekend vanaf het ontsteken van de eerste trap tot aan het moment van inslag van de tweede trap. (5 punten). Als je de eindsnelheid onder vraag e) niet hebt kunnen berekenen, neem dan aan $Ve_2 = 2922$ m/s.

N.B. Afleidingen van formules, zoals de vergelijking van Tsiolkowski, zijn niet vereist maar kunnen wel behulpzaam zijn bij het vinden vande juiste uitdrukkingen.

Bij vraagstukken 4 en 5 mag, zonder afleiding, gebruik worden gemaakt van de volgende vergelijkingen:

$$r = \frac{a(1-e^2)}{1+e\cos\theta} = a(1-e\cos E) \qquad (1)$$

$$M = E - e\sin E \qquad (2)$$

$$\frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a} \qquad (3)$$

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} \qquad (4)$$

$$\Delta\omega = \frac{3}{2}\pi J_2 \left(\frac{R_e}{p}\right)^2 (5\cos^2 i - 1)\ (\textit{per omloop}) \qquad (5)$$

$$\Delta\Omega = -3\pi J_2 \left(\frac{R_e}{p}\right)^2 \cos i(\textit{ per omloop}) \qquad (6)$$

Verder zijn de volgende parameters gegeven:

- Gemiddelde straal van de Aarde: $R_e = 6371$ km
- Gemiddelde straal van Venus: $R_{Venus} = 0.72\ R_e$
- Gravitatieparameter van de Aarde: $\mu_e = 398600\ \text{km}^3/\text{s}^2$
- Gravitatieparameter van Venus: $\mu_{Venus} = 0.82\ \mu_e$
- Gravitatieparameter van de Zon: $\mu_{Sun} = 1.3271 \times 10^{11}\ \text{km}^3/\text{s}^2$
- Afstand Aarde-Zon : $r_e = 1$ AU
- Afstand Venus-Zon: $r_{Venus} = 0.723$ AU
- 1 AU = 150×10^6 km
- Tweede zonaal harmonische coefficient: $J_2 = 1.082627 \times 10^{-3}$

Waardering:
- vraag 4: 20 punten
- vraag 5: 15 punten

Vraagstuk 4. Interplanetaire vlucht naar Venus

Beschouw een satellietmissie van de Aarde naar Venus. De interplanetaire vlucht vindt plaats d.m.v. een Hohmann overgangsbaan.

a. Wat is de omlooptijd van de Aarde om de Zon? En die van Venus? (antwoord in jaren).

b. Waar bevindt zich het apocentrum van de overgaangsbaan? En waar het pericentrum?

c. Bereken de reistijd van de Aarde naar Venus.

d. Bereken de synodische periode voor het Venus-Aarde-Zon systeem.

e. Bereken de minimale wachttijd (ofwel de tijd dat de satelliet om Venus mag cirkelen) alvorens de satelliet terug kan reizen naar de aarde d.m.v. wederom een Hohmann overgansbaan. Wat is de minimale missieduur?

Vraagstuk 5. Stoorkrachten

Stoorkrachten, d.w.z. krachten die afwijken van de centrale gravitatiekracht, zorgen ervoor dat de baan van een satelliet rond de aarde afwijkt van een perfecte kegelsnede. Deze stoorkrachten kunnen in sommige situaties ten voordele worden gebruikt.

Zon-synchrone satellietbanen:

a. Wat is een zon-synchrone baan?

b. Noem minimaal twee mogelijke voordelen van het vliegen in een dergelijke baan (denk dan met name ook aan een zgn. "dawn-dusk" baan, waarbij de lokale tijd bij evenaarspassages 6 uur 's morgens of 's middags is).

c. Bereken de inclinatie van een cirkelvormige satellietbaan op 200 km hoogte rond de aarde.

De perigeumhoek van satellieten die vliegen in een baan met kritische inclinatie is constant.

d. Bereken de kritische inclinaties.

e. Leg uit hoe Rusland handig gebruikt maakt van deze kritische inclinatie voor haar *Molnya* communicatiesatellieten.

EXAM AE1-801, **SPACE ENGINEERING & TECHNOLOGY I**

29 August 2005

09:00 – 12:00 hrs

This exam consists of 5 problems with several items. Start each problem on a fresh sheet of paper. Remember to clearly indicate your name and student number on each sheet. Show in your answers also the formulae that you are using. Insert the numerical values you use stepwise.

Problem 1 (18 points; 30 minutes)

This problem (1) is related to the part *Space Missions & Systems* of the course *ae1-801.*

We want to observe the complete radiation spectrum of celestial bodies for long periods of time from space. It seems attractive to go far from the Earth, as

- The Earth itself is a source of radiation (heat and reflected sun light)
- Close to Earth the time, during which a celestial body (a point in inertial space) can be observed uninterruptedly, is limited (the Earth passes through the satellite – object line)
- We have long contact periods with the ground station, so we need less on-board storage of data, less sophisticated autonomy and see "cosmic" events in real-time.

There are however also disadvantages.

Questions

List the disadvantages of this concept from the following points of view:

1a Space environment

1b Launch capacity

1c Communication

1d Pointing accuracy

1e Electrical power

1f Orbit and altitude control

Be specific in your answers; give a rationale for each disadvantage you can identify.

Problem 2 (7 points; 15 minutes)

This problem (2) is related to the part *Space Missions & Systems* of the course *ae1-801.*

A robot arm of 10 m length has to move a payload of 6000 kg mass. The actuator at the root of the arm exercises 300 Nm torque.

2a How fast has the robot arm moved the payload over 180 degrees?

2b To save electrical power the actuator is a small motor with a reduction gearbox (gear ratio 1:400). What is the motor torque?

Problem 3 (40 points)

This problem (3) is related to the part *Rocket Motion* of course *ae1-801.*

The newly developed two-stage rocket Fire Flash-2 just had its second test flight. The first stage has 2 identical engines and the second stage only one of exactly the same type. Due to an anomaly in the first stage one of its engines did not ignite. As a result the rocket did not lift off immediately, but only after its weight had diminished to the point where it balanced the thrust. The remaining engine then continued to function until all propellants were consumed. The second stage ignited immediately after burnout of the first stage. This stage performed nominally. At the moment of second stage burnout the tracking station measured an altitude of 142 km above sea level.

You have gotten the task to evaluate the performance and the consequences of the failure:

1. What has been the maximum velocity of the second stage at burnout?
2. How many seconds after ignition of the first stage (t_0) did the second stage crash on the ground?

The Fire Flash-2 is a 2-stage rocket. To economize on costs, both stages are identical in absolute mass and propellant mass. The only difference is that the first stage has two identical engines and the second stage only one. Each stage has a construction mass of 750 kg and a propellant mass of 4250 kg. The rocket carries a payload of 500 kg.

The following design parameters are available:

Thrust of each engine (3 in total)	F = 80 kN
Specific impulse of the engines	I_{sp} = 300 s
Gravitational acceleration	g_0 = 9.81 m/s2

For simplicity, you may assume that the rocket moves perfectly vertical throughout the flight and the flight takes place in a homogeneous gravity field ($g = g_0$ = constant) in vacuum.

a. Compute the total mass of the rocket (2 pts)
b. Compute the actual burn time of both stages (2 pts)
c. Compute the time until the rocket actually lifts-off the launch pad (4 pts)
d. Analyse the problem and list the consecutive calculation steps (N.B. 3) that are necessary to calculate the velocity of the second stage at burnout (8 pts)
e. Follow the calculations steps you have listed under d) and calculate the velocity of the second stage at burnout. (14 pts)
f. List the consecutive calculation steps that are necessary to calculate the total duration of the test flight after ignition of the first stage (t_0) until the second stage crashes on the ground. (5 pts)
g. Follow the calculations steps you have listed under f) and calculate the total flight duration after ignition of the first stage until the second stage crashes on the ground. (5 pts).
If you did not succeed in calculating the velocity under question e), please assume Ve_2 = 2922 m/s.

N.B. Derivations of formulae like Tsiolkowski's equation are not requested, but may be helpful to find the correct expressions.

For problems 4 and 5 the following equations may be used without derivation:

$$r = \frac{a(1-e^2)}{1+e\cos\theta} = a(1-e\cos E) \tag{1}$$

$$M = E - e\sin E \tag{2}$$

$$\frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a} \tag{3}$$

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{4}$$

$$\Delta\omega = \frac{3}{2}\pi J_2\left(\frac{R_e}{p}\right)^2(5\cos^2 i - 1)\ (\textit{per orbital revolution}) \tag{5}$$

$$\Delta\Omega = -3\pi J_2\left(\frac{R_e}{p}\right)^2\cos i(\ \textit{per orbital revolution}) \tag{6}$$

Furthermore, the following parameters are given:

- Mean radius of the Earth: $R_e = 6371$ km
- Mean radius of Venus: $R_{Venus} = 0.72\ R_e$
- Gravity parameter of the Earth: $\mu_e = 398600\ \mathrm{km^3/s^2}$
- Gravity parameter of Venus: $\mu_{Venus} = 0.82\ \mu_e$
- Gravity parameter of the Sun: $\mu_{Sun} = 1.3271 \times 10^{11}\ \mathrm{km^3/s^2}$
- Distance Earth-Sun : $r_e = 1$ AU
- Distance Venus-Sun: $r_{Venus} = 0.723$ AU
- 1 AU = 150×10^6 km
- Second zonal harmonic coefficient: $J_2 = 1.082627 \times 10^{-3}$

Grading:
- Problem 4: 20 points
- problem 5: 15 points

Problem 4. Mission to Venus

Consider a satellite mission from the Earth to Venus. The interplanetary flight from the Earth to Venus is conducted by means of a Hohmann transfer orbit.

a. Derive the orbital revolution periods (in years) of the Earth and Venus around the Sun.

b. What is the apocenter location and what is the pericenter location of the Hohmann transfer orbit?

c. Compute the travel time from the Earth to Venus.

d. Compute the synodic period for the Venus-Earth-Sun constellation.

e. Compute the minimum lay-over time (or the time the satellite has to wait while circling around Venus) in case the satellite has to travel back to the Earth by again a Hohmann transfer. What is the total minimum mission duration?

Problem 5. Perturbing forces

Perturbing forces, i.e. forces that deviate from the central gravity field term, cause a satellite's orbit around the Earth to deviate from a perfect Keplerian orbit. These perturbing forces can sometimes be advantageous for certain satellite orbits around the Earth.

Sun-synchronous satellite orbits:

a. What is a sun-synchronous orbit?

b. Give at least two possible advantages of flying a sun-synchronous orbit (consider especially so-called "dawn-dusk" orbits with a local time of 6 AM or 6 PM at equator crossings).

c. Compute the inclination of a sun-synchronous circular orbit at 200 km altitude above the Earth.

The argument of perigee of satellites flying in an orbit with *critical inclination* is constant.

d. Compute the *critical inclinations.*

e. Explain how Russia used this *critical inclination* to her advantage when designing the *Molnya* orbits for telecommunication.

EXAM AE1-801, SMS; SPACE ENGINEERING & TECHNOLOGY I

14 JUNE 2005

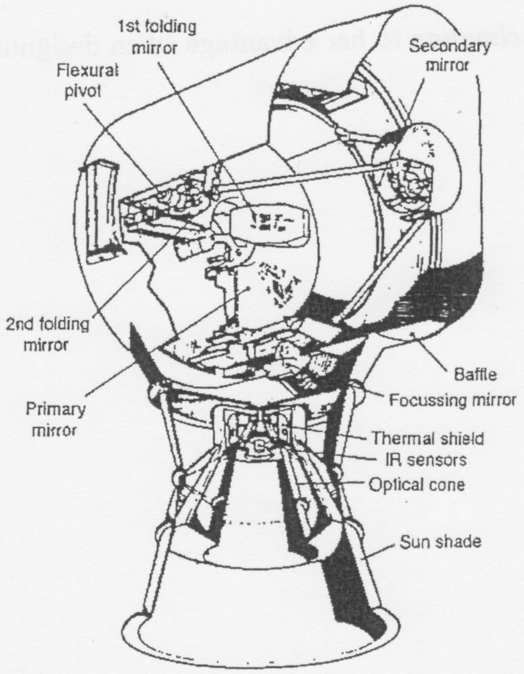
09:00 – 12:00 hrs

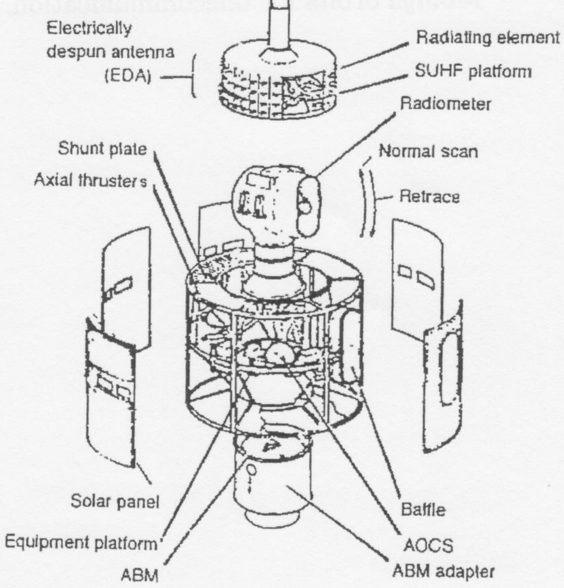
This exam consists of 4 problems with several items. Start each problem on a fresh sheet of paper. Remember to also clearly indicate your name and student number on each sheet. Show in your answers also the formulae that you are using. Insert the numerical values you use stepwise.

Problem 1 (25 points; 45 minutes)

This problem (1) is related to the part *Space Missions & Systems* of the course *ae1-801.*

Meteosat is a geostationary satellite at an altitude h_{GEO} of 35850 km, spinning at 100 revolutions per minute; its spin axis normal to the orbit plane. The sensor "scans" the Earth once each revolution (one "line") and builds one Earth image every 30 minutes





in visible and IR bands. After each scan (revolution) the sensor mirrors are adjusted, such that the next line is scanned during the next revolution. The satellite sends the images and other data collected from Earth located platforms to Earth. Its mass distribution is:

- 362 kg dry mass,
- 39 kg hydrazine propellant for attitude and orbit control,
- Apogee Boost Motor (ABM) propellant mass of 360 kg.

The resolution of the earth image is 2.5 km in the visual channel (VIS) and 5 km in the infra-red channel (IR)

Questions

1a Draw a picture of the Earth and Meteosat in its orbit, indicating the Earth radius R_{EARTH}, the orbit altitude h_{GEO} and the half cone angle α_{GEO} the Earth is included in, when seen from the satellite.

1b Calculate the diameter of the Earth disc D_s as seen by Meteosat, assuming the Earth radius R_{EARTH} equals 6370 km and the geostationary orbit altitude h_{GEO} equals 35850 km. Calculate also α_{GEO}.

1c What is the most Northern or Southern latitude of the Earth, that is visible from Meteosat?

1d How many geostationary satellites would be needed to cover the whole Earth between these latitudes? Motivate your answer.

1e Calculate how many pixels N_{E-W} the line of the image on the equator of the Earth disc contains in the visual channel (use the VIS resolution).

1f What is the time needed to build up one line of the image?

1g Assuming the pixels have equal size in North-South and East-West direction and that the image of the earth is a square, calculate how many pixels the image of the Earth disc contains in the visual channel (use the VIS resolution).

1h If we assume that each pixel uses 8 bits, how many bits contains one Earth image?

1i What is the minimum bit rate for sending one full Earth image to a ground station?

1j Each revolution of the satellite one line of the Earth image is scanned. Deduce from the answer on 1g how many lines the Earth image has.

1k In how much time is one full image of the Earth disc build up (using the results of 1j)? Is this compatible with the time available to build up one image?

1l Assume now that 2 pixels in North-South direction are scanned per scan and that the mirrors are stepping 2 North-South pixels per revolution. How much time is takes now to produce one full Earth image?

1m How much time is left after completion of the scan according to 1l? For what purpose this time will be used in your opinion?

1n What is the bit rate corresponding to the infra-red channel of Meteosat (use the infra-red channel resolution)?

1o Assuming Meteosat has three visual and one infra-red channel: what is the total minimum bit rate of Meteosat?

Problem 2 (40 points)

This problem (2) is related to the part *Rocket Motion* of the course *ae1-801*.

The newly developed two-stage rocket Fire Flash-2 just had its first test flight. The first stage has 2 identical engines and the second stage only one of exactly the same type. Due to an anomaly in the first stage one of its engines shut down exactly half way through the nominal burn time. The remaining engine continued to function until all propellants were consumed. Then immediately the second stage ignited. This stage performed nominally. At the moment of second stage burnout the tracking station measured an altitude of 198 km above sea level.

You have gotten the task to evaluate the performance and the consequences of the failure:

1. What has been the maximum velocity of the second stage at burnout?
2. How many seconds after ignition of the first stage (t_0) did the second stage crash on the ground?

The Fire Flash-2 is a 2-stage rocket. To economize on costs, both stages are identical in absolute mass and propellant mass. The only difference is that the first stage has two identical engines and the second stage only one. Each stage has a construction mass of 750 kg and a propellant mass of 4250 kg. The rocket did not carry any payload.

The following design parameters are available:

Thrust of each engine (3 in total)	$F = 75$ kN
Specific impulse of the engines	$I_{sp} = 300$ s
Gravitational acceleration	$g_0 = 9.81$ m/s2

For simplicity, you may assume that the rocket moves perfectly vertical throughout the flight and the flight takes place in a homogeneous gravity field ($g = g_0 =$ constant) in vacuum.

a. Compute the nominal burn time of both rocket stages (4 pts)

b. Analyse the problem and list the consecutive calculation steps (N.B. 3) that are necessary to calculate the velocity of the second stage at burnout (8 pts)

c. Follow the calculations steps you have listed under b) and calculate the velocity of the second stage at burnout. (18 pts)

d. List the consecutive calculation steps that are necessary to calculate the total duration of the test flight after ignition of the first stage (t_0) until the second stage crashes on the ground. (5 pts)

e. Follow the calculations steps you have listed under d) and calculate the total flight duration after ignition of the first stage until the second stage crashes on the ground. (5 pts).
If you did not succeed in calculating the velocity under question c), please assume $Ve_2 = 4350$ m/s.

N.B. Derivations of formulae like Tsiolkowski's equation are not requested, but may be helpful to find the correct expressions.

The problems (3) and (4) are related to the part *Orbital Mechanics* of the course *ae1-801.*

For problems 3 and 4 the following equations may be used without derivation:

$$r = \frac{a(1-e^2)}{1+e\cos\theta} = a(1-e\cos E) \tag{1}$$

$$M = E - e\sin E \tag{2}$$

$$\frac{V^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a} \tag{3}$$

$$T = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{4}$$

$$\Delta\omega = \frac{3}{2}\pi J_2 \left(\frac{R_e}{p}\right)^2 (5\cos^2 i - 1) \textit{ (per orbital revolution)} \tag{5}$$

$$\Delta\Omega = -3\pi J_2 \left(\frac{R_e}{p}\right)^2 \cos i \textit{(per orbital revolution)} \tag{6}$$

Furthermore, the following parameters are given:

- Mean radius of the Earth: $R_e = 6371$ km
- Mean radius of Saturn: $R_{Saturn} = 9.51\ R_e$
- Gravity parameter of the Earth: $\mu_e = 398600$ km^3/s^2
- Gravity parameter of Saturn: $\mu_{Saturn} = 95.2\ \mu_e$
- Gravity parameter of the Sun: $\mu_{Sun} = 1.3271 \times 10^{11}$ km^3/s^2
- Distance Earth-Sun : $r_e = 1$ AU
- Distance Saturn-Sun: $r_{Saturn} = 9.555$ AU
- 1 AU = 150×10^6 km
- Second zonal harmonic coefficient: $J_2 = 1.082627 \times 10^{-3}$

Grading:
- Problem 3: 20 points
- problem 4: 15 points

Problem 3. Mission to Saturn

Consider a satellite mission from the Earth to Saturn. The interplanetary flight from the Earth to Saturn is conducted by means of a Hohmann transfer orbit.

a. Derive the orbital revolution periods (in years) of the Earth and Saturn around the Sun.

b. What is the apocenter location and what is the pericenter location of the Hohmann transfer orbit?

c. Compute the travel time from the Earth to Saturn.

d. Compute the synodic period for the Saturn-Earth-Sun constellation.

e. Compute the minimum lay-over time (or the time the satellite has to wait while circling around Saturn) in case the satellite has to travel back to the Earth by again a Hohmann transfer. What is the total minimum mission duration?

Problem 4. Perturbing forces

Perturbing forces, i.e. forces that deviate from the central gravity field term, cause a satellite's orbit around the Earth to deviate from a perfect Keplerian orbit. These perturbing forces can sometimes be advantageous for certain satellite orbits around the Earth.

Sun-synchronous satellite orbits:

a. What is a sun-synchronous orbit?

b. Give at least two possible advantages of flying a sun-synchronous orbit (consider especially so-called "dawn-dusk" orbits with a local time of 6 AM or 6 PM at equator crossings).

c. Compute the inclination of a sun-synchronous circular orbit at 700 km altitude above the Earth.

The argument of perigee of satellites flying in an orbit with *critical inclination* is constant.

d. Compute the *critical inclinations*.

e. Explain how Russia used this *critical inclination* to her advantage when designing the *Molnya* orbits for telecommunication.

EXAM AE1-801, SMS; TEST **English**

SPACE ENGINEERING & TECHNOLOGY I

PART SPACE MISSIONS & SYSTEMS

5 NOVEMBER 2004; 14:00-16:00

This exam consists of 5 problems with several items. Start each problem on a fresh sheet of paper. Remember to clearly indicate your name and student number on each sheet. Show in your answers also the formulae that you are using. Insert the numerical values you use stepwise.
You are supposed to make the exam individually and you may not use books, lecture notes or your own notes with this exam.

PROBLEM 1 (29 points; 35 minutes)

Launchers for Galileo

Galileo is the European equivalent of the Global Positioning System, a satellite based navigation system. It consists of 30 satellites in medium altitude Earth orbits (MEO) of 23222 km altitude. The satellites are equally distributed over 3 orbit planes (so 10 satellites in each orbit plane) with an inclination of 56 degrees. One satellite has a mass of 635 kg, and per satellite 115 kg supporting structure is needed to attach it to the launcher. One satellite costs 30 M$.

1a What is the overall launch mass of one satellite?

You have to select the launcher for the 30 satellites and three candidate launchers have been identified with the following performance and cost:

Launcher	*Cost (M$)*	*Reliability*	*Satellite mass in MEO (kg)*
Ariane 5	125	0.90	5800
Proton K	70	0.85	4900
Long March 2E	47	0.75	1560

Each of these launchers may launch one or more satellites at the same time up to the satellite mass in MEO.

1b Compute for each of the three launchers the cost per kg payload in MEO. Which launcher is the cheapest according to this calculation?

1c How many launchers of each kind do you need to launch the 30 satellites, without taking into account the reliability and assuming that you have sufficient time available to transfer Galileo satellites from one orbit plane to another?

1d Calculate for each of the three launcher types the required number launch vehicles, taking into account the reliability (so also the loss of satellites) and again assuming that you have sufficient time available to transfer Galileo satellites from one orbit plane to another.

1e What is for each of the three launchers the total launch cost, taking into account extra launch vehicles as a consequence of failures to be expected (and also the cost of extra satellites)? Which launcher do you select? Motivate your answer with numerical results.

1f Do you think it is wise to select one type of launcher to get the satellites in orbit? Motivate your answer.

1g Can you think of a way to exploit the unused launch capacity of the launchers considered? Are they all equally attractive from this point of view?

PROBLEM 2 (16 points; 19 minutes)

Dutch Astronomy Satellites

The first two Dutch satellites ANS and IRAS both were astronomy satellites.

2a Which objects have been observed by ANS and IRAS? Which physical properties of these objects have been studied? Why have they been studied from space?

2b In what kind of orbit have ANS and IRAS been placed? Draw a picture of the Earth and the orbit and indicate the Earth's North and South Pole, the direction of the Sun and the viewing direction of the instruments (telescopes) in the drawing. Mention two advantages of such an orbit. Can you also mention a disadvantage of this orbit?

Assume that the viewing direction of the IRAS telescope is in the plane normal to the sun direction.

2c The IRAS instrument has a field of view of 1 degree. What is the minimum time it takes IRAS to map the total sky, neglecting the yearly variation of the angle between sun vector and equatorial plane?

2d Where should the IRAS ground station be located to have maximum contact time with the satellite?

PROBLEM 3 (30 points; 36 minutes)

Launching a Satellite by means of a Single Stage Launcher

A small satellite will be launched in a low, circular orbit with an altitude h_E of 500 km. The assignment is to determine the feasibility to do this with single stage launcher. The Earth radius R_E equals 6370 km.

3a Calculate the orbital velocity V_{500} in that low earth orbit, taking into account that the orbital period equals 94.62 minutes.

3b During launch the rocket "loses" velocity due to the gravity forces. This velocity loss is:

$$\Delta V_g = \int_{t=o}^{t=t_b} -g(t)\cdot\sin(\gamma(t))\cdot dt$$

where *g(t)* is the acceleration due to gravity at time *t*, $\gamma(t)$ is the angle between the velocity vector of the launcher and the horizontal and t_b is the burning time of the rocket engine. At the start of the launcher γ equals 90°, when the engine stops (at the injection in the circular orbit) γ equals 0°. An acceptable assumption is that during the full flight $g(t).sin(\gamma(t))$ has an average value equal to $0.5\ g_0$.

Can you list another loss occurring during the launcher ascent?

3c Calculate the velocity loss (gravity loss) ΔV_g during the launch, assuming a rocket engine burning time t_b of 5 minutes.

3d The loss due to air drag during the flight equals 350 m/s. What is the total velocity increment V_{total} that the launcher has to give to the satellite?

3e The launcher uses as propellants liquid hydrogen and oxygen, one of the most energetic chemical propellant combinations. The combustion products have an exhaust velocity w_e of 4200 m/s and the launcher has an empty mass M_e of 2500 kg, while carrying 12500 kg propellants. Calculate with Tsiolkowski the ideal final velocity of the rocket.

3f Can this rocket bring the satellite in the 500 km orbit?

3g Which conclusion do you draw from the results of the calculations?

PROBLEM 4 (16 points; 19 minutes)

Personal Communication Systems (Mobile Telephones)

List the disadvantages and advantages of each of the following personal communication systems:

d. A system using geo-stationary satellites

e. A system like Iridium

f. A fully land-based system (GSM)

Address both space and ground segment. Consider aspects like coverage, transmission power, mass, number of launches, etc. Present the results in a table, as shown below. Keep your answer short and concise.

Aspect ⇓	*A system using geo-stationary satellites*	*A system like Iridium*	*A fully land-based system (GSM)*

EXAM AE1-801, SMS; TEST **English**

PROBLEM 5 (9 points; 11 minutes)

Give the definition of the following terms and illustrate with a drawing, when useful:

5a Geo-stationary orbit

5b Perigeum

5c Libration point

5d Elevation

5e Booster