3. Attitude and orbit Control System

3.1 General A1 p 62, 68

a) attitude of a spacecraft: its orientation in space

b) function of att. determ. syst. = measuring and computing the orientating of the spacecraft rel. to certain reference

c) function of att. control syst.: orienting the spacecraft in a specified predetermined direction

d) = a)

e) controllers, actuators, sensors

f) spin stabilization, dual spin st., gravity gradient st., aerodynamic st., magnetic st.

3.2 Three-Axis Stabilisation A 1 pg 76, 96, 97

a) slide 31 & 72
b) slide 73, 74 $K_P > 0$ en $K_D > 0$

3.3 Gravity Gradient Stabilisation

a) Stable: $\underset{y}{I_{pitch}} > \underset{x}{I_{roll}} > \underset{z}{I_{yaw}}$ en $I_{zz} > I_{yy} > I_{xx}$

$\Rightarrow$ $I_{zz} = I_{pitch}$: De Z-as staat ⊥ op het baanopp.
$I_{yy} = I_{roll}$: De Y-as is gericht i/d voortbewegingsrichting v/h object vallend a/h baanopp.
$I_{xx} = I_{yaw}$: De X-as is in het baanopp. gelegen, gericht naar de aarde.

→ zie workbook solutions

b) $I_{xx} - I_{zz} > 0$ (stabilisatie voorwaarden)

$$3k_x + k_x k_z + 1 > 0$$
$$3k_x + k_x k_z + 1 > 4\sqrt{k_x k_z}$$
$$k_x k_z > 0$$

$$\begin{cases} k_x = \dfrac{I_{yy} - I_{zz}}{I_{xx}} \\ k_z = \dfrac{I_{yy} - I_{xx}}{I_{zz}} \end{cases}$$

$\rightarrow 7465084 - 983159 = 6482925 > 0$

~~Zie Workbook Solutions~~

34 $\rightarrow k_x = \dfrac{I_{yy} - I_{zz}}{I_{xx}}$; $k_z = \dfrac{I_{yy} - I_{xx}}{I_{zz}}$

However, since above conditions were obtained by assuming that I_{yy} is the largest moment of inertia (I_{zz} in our case), I_{zz} is the smallest moment of inertia (I_{xx} in our case), and I_{xx} is the intermediate moment of inertia (I_{yy} in our case), k_x and k_x have to be changed to

$$k_x = \frac{I_{zz} - I_{xx}}{I_{yy}} \; ; \; k_z = \frac{I_{zz} - I_{yy}}{I_{xx}}$$

And condition $I_{xx} - I_{zz} > 0$ has to be changed to $I_{yy} - I_{xx} > 0$

$$\Rightarrow k_x = \frac{7747582 - 953159}{7465084} = 0,91016$$

$$\rightarrow k_z = \frac{I_{zz} - I_{yy}}{I_{xx}} = \frac{7747582 - 7465084}{953159} = 0,29638$$

these results → substitution in stab. conditions

$3 k_x + k_x k_z = 3 \times 0,91016 + 0,91016 \times 0,29638 + 1$
$= 4 > 0$ ✓

$3 k_x + k_z k_z + 1 = 3 \times 0,91016 + 0,91016 \cdot 0,29638$
$= 4 > 2,0775 = 4 \sqrt{k_x k_z}$ ✓

$k_x k_z = 0,2695 > 0$ ✓

and $I_{yy} - I_{xx} = 7465084 - 953159 = 6611925 > 0$

therefore, S/S is stable with the orientation given in account

3.4 Actuator Design : Reaction Wheels

a) max. dist. torque (pg 85 A1)

* gravity gradient : $M_g = \frac{3\mu}{2R^3} \left| I_{yaw} - I_{min} \right| \sin 2\theta$ $\quad \mu \rightarrow 3,986 \cdot 10^{14}\ m^3/s^2$

$$= \frac{3 \cdot 3,986 \cdot 10^{14}}{2 \cdot (700 + 6378)^3 \cdot 10^9} \left| 75 - 45 \right| \sin(2 \cdot \theta)$$

$$= 4,38 \cdot 10^{-5}\ Nm$$

* solar radiation : $M_a = \frac{(c_{ps} - c_g) \cdot F_s A_s (1+q) \cos i}{c}$

$$= \frac{1358 \cdot \overset{1+q}{(1,6)} \cdot 1,4^2 \cdot \cos 0 \cdot 0,3}{3 \cdot 10^8}$$

$$= 4,26 \cdot 10^{-6}\ Nm$$

* magnetic field $\quad M_m = D \cdot B$

$$= \frac{2 \cdot DM}{R^3} = \frac{2 \cdot 1 \cdot 7,96 \cdot 10^{15}}{(700 + 6378)^3 \cdot 10^9}$$

$$= 4,49 \cdot 10^{-5}$$

* aerodynamic : $M_a = 0{,}5\,[\rho\, C_d\, A V^2]\,(c_{pa} - c_g)$

SMAD
achteraan!

$= 0{,}5 \cdot 2{,}5 \cdot 0{,}3 \cdot 3{,}73 \cdot 10^{\overset{-14}{\textcircled{-13}}} \cdot 1{,}4^2 \cdot 7904{,}3^2$

$= 1{,}13 \cdot 10^{-6}\ Nm$

~~⇒~~ max dist. torque : $4{,}49 \cdot 10^{-5}\ Nm$ → magnetic

b) Slew torque : $M = \dfrac{4\,\theta \cdot \textcircled{I}}{t^2}$ → welke → grootste

$= \dfrac{4 \cdot \frac{\pi}{6} \cdot 75}{600^2}$

$= 4{,}36 \cdot 10^{-4}\ Nm$

4. Power System :

4.1 Energy Source

* ~~A~~ A.1 , pg 122 !

* A.1 , pg 123

$S = \dfrac{3 \times 10^{25}}{R^2}$

→ earth : $1{,}34 \cdot 10^3\ W/m^2$
→ mercury : $8{,}95 \cdot 10^3\ W/m^2$
→ mars : $577{,}6\ W/m^2$
→ pluto : $0{,}862\ W/m^2$

zie waarden SSE : pg 37

4.2 Solar Array Sizing

p. 132 A1

a) $P_{SA}\, t_d = \frac{P_e\, t_e}{X_e} + \frac{P_d\, t_d}{X_d}$

$t_e = 69{,}4$ min

$t_d = 1436{,}1 - 69{,}4$ min

$= 1366{,}7$ min

$P_e = P_d = 2{,}8\,kW$

$X_e = 0{,}65$

$X_d = 0{,}85$ (dictaat)

$$P_{SA} = \frac{\frac{2800 \cdot 69{,}4}{0{,}65} + \frac{2800 \cdot 1366{,}7}{0{,}85}}{1366{,}7}$$

$\Rightarrow P_{SA} = 3513\,W$

b) $L_d = (1-d)^x$ met $x = 10$ jaar

d = degradation $= 0{,}03$

$L_d = (1-0{,}03)^{10}$

$= 0{,}7374$

c) $A_{SA} = \frac{P_{SA}}{P_{EOL}} = \frac{P_{SA}}{P_{BOL} \cdot L_d} = \frac{P_{SA}}{L_d\, P_0 \cdot I_d \cdot \cos\theta}$ zie 132

$P_{SA} = 3513\,W$

$L_d = 0{,}7374$

$P_0 = 0{,}9 \cdot 0{,}14 \cdot (1358\,W/m^2) = 171{,}1\,W/m^2$

$I_d = 0{,}77$

$\cos \underset{\overset{\shortparallel}{0}}{\theta} = 1$

$$A_{SA} = \frac{3513}{0{,}7374 \cdot 171 \cdot 0{,}77 \cdot 1} = 36{,}2\,m^2$$

d) $n = \frac{V_{bus}}{V_{cell}} = \frac{28}{0{,}35} = 80$

$mV = V \cdot 10^{-3}$

e) $m = n \cdot \frac{m}{n} =$

P_0 met $A = (0{,}02 \cdot 0{,}04)$ (m^2)

$\rightarrow 171{,}1 \cdot 8 \cdot 10^{-4} = 136{,}8\ mW$ per cell

$\rightarrow P_{Ea} = 136{,}8 \cdot 0{,}7374 = 0{,}100\ 876\ W$ per cell

$P_{req} = 3513\ W$ → nr of cells $\frac{3513}{0{,}100876} = 34833{,}81$

There are 80 cells in each string (zie d)

$\Rightarrow m = \frac{34833{,}81}{80} \approx 435{,}4 = 436$ strings

4.3 DUT Sat Battery Sizing

a) $P_{batt.\,req.} = \frac{300}{0{,}8} = 375\ W$

per batt. : $\frac{28}{0{,}8} = 35\ V$

b) $I_d = \frac{P_e}{V_{bus}} = \frac{300}{28} = 10{,}7\ A$

c) N_{batt} (= nr of batt. cells) $= \frac{35}{1{,}2} = 29{,}2$ cells → 30 cells!

$V_{batt.} = 30 \cdot 1{,}2 = 36\ V$

d) at most one ellips period per orbit. ⇒ lifetime most eclips is total number of orbits.

$$N_e = \frac{\overset{t_{dag}}{24 \times 60}}{\underset{t_{orbit}}{105}} \cdot \overset{dagen}{365} \cdot \overset{jaren}{5} \simeq 25028$$

e) pg 149 figuur! A1

=) 25000, tussen 10^4 en 10^5, NiCd (zie geg)
=) ± 20% DOD

80% of the total battery charge is left unused.

~~f) $C = \frac{E}{V_{bat}}$~~

g) $E = \frac{P_{bat} \cdot t_e}{DOD} = \frac{375 \cdot \frac{35}{60}}{0,2} = 1094\,Wh$

f) battery cap. $C = \frac{E}{V_{bat}} = \frac{1094}{36} = 30,4\,Ah$

h) mass: $M_{batt} = \frac{E}{E_{sp}} = \frac{1094}{35} = 31,25\,kg$

↳ in Syllabus: specific energy for NiCd batteries between 30-40 Wh/kg

E_v (energy density) between 80-110 Wh/l

$V_{batt} = \frac{E}{E_v} = \frac{1094}{95} = 11,5\,l$

over whole range M between 27-37 kg & V between 10-14 l

i) $t_{charge} = t_{orbit} - t_e = 105 - 35 = 70\,min$

j) $P_{SA_{ch}} = \frac{P_{batt}\ t_e}{t_d \cdot \eta_d} = \frac{375 \cdot 35/60}{\frac{70}{60} \cdot 0,85} = 220\,W$

k) $I_{ch} = \frac{P_{SA\,ch}}{N\,V_{ch}} = \frac{220}{30 \cdot 1,5} = 4,9\,A$

↳ # cells ↳ Volt (end of ch)

500W + 1,1 kW ^ hoe komt ge daar aan

4.4 Sizing of Power Subsystem of Electrically prop. vehicle

a) $$P_{SA} = \frac{\frac{P_e t_e}{x_e} + \frac{P_d t_d}{x_d}}{t_d}$$

$P_e = 1600 = P_d$

$t_e = 69$ min

$t_d = 1440 - 69 \rightarrow (24 \times 60)$

$= 1371$ min

$x_e = 0,65$

$x_d = 0,85$

$$P_{SA} = \frac{\frac{1600W \cdot 69\,min}{0,65} + \frac{1600W\ 1371\,min}{0,85}}{1371\ min} = 2005\ W$$

$$\Rightarrow A_{SA} = \frac{P_{SA}}{P_{EOL}} = \frac{2005\ W}{150\ W/m^2} = 13,4\ m^2$$

b) $P_e = 1,25\,kW + 500W = 1750\ W = P_d$

$t_d = (89-37)$ min

$t_e = 37$ min

$x_e = 0,65$

$x_d = 0,85$

$$\Rightarrow P_{SA} = \frac{\frac{1750 \cdot 37\,min}{0,65} + \frac{1750 \cdot (89-37)\,min}{0,85}}{(89-37)\ min} = 3974$$

$$L_d = (1-0,02)^8 = 0,85 \Rightarrow P_{BOL} = \frac{150}{0,85} = 176$$

$$\Rightarrow A_{SA} = \frac{3974}{176} = 22,5\ m^2$$

c) $$C = \frac{E}{V_{bat}} = \frac{P_{bat} \cdot t_e}{DOD \cdot V_{bat}} = \frac{1750 \cdot \frac{37}{60}}{0,6 \cdot 0,85} = 2,1\ kWh$$

d) Peak power tracking (PPT)

Shunt regulation (SR) or switching off parts of the solar wings

(A2) p 6

Hoofdstuk 5: Telecommand and Telecomm.

5.1 Decibels

dB:

① $E_b = 100\,\mu W$, $N_0 = 1\,\mu W$. How many $dB\left(\frac{E_b}{N_0}\right)$?

$$10 \log_{10} \frac{E_b}{N_0} = 10 \log_{10} \frac{100}{1} = 20\ dB$$

② dBi:

gain $G = 100$, transmitter power is 100 W

$$10 \log_{10} G = 10 \log_{10} \frac{P_{antenna}}{P_{isotropic}} \left(\frac{PG/4\pi R^2}{P/4\pi R^2}\right) = 20\,dBi$$

③ dBW and dBm:

$P_A = 1000\,W$ in dBW & dBm(W)

$$\Rightarrow 10 \log_{10} P_A = 10 \log_{10} \frac{1000}{1} = 30\ dBW = 10 \log_{10} \frac{1000}{0{,}001} = 60\,dBm$$

band ?!

hoe berekenen?
- tekenen?

5.2 Free space loss for a GEO stationary s/c

$$L_s = \left(\frac{\lambda}{4\pi \underset{\substack{\shortparallel \\ h}}{S}}\right)^2 = \left(\frac{\cancel{2\pi}\, c}{4\pi\, h\, f}\right)^2$$

C band : f = 4 - 8 GHz
X band : f = 8-12 GHz
Ku band : f = 12 - 18 GHz
K band : f = 18 - 26 GHz
Ka band : f = 26 - 40 GHz

in dB $\Rightarrow$ $10 \log_{10}$ (without) = with [dB]

5.3 EIRP and Flux Density

geg: $P_t = 100 W$

$G_t = 30 dBi$

$h = 36000 \cdot 10^3 m$

a) EIRP of transmitter?

$$EIRP \overset{= P_t + G_t}{=} P_t [dBW] + G_t [dBi]$$

$$= 10 \log (100) + 30 = 20 dBW + 30 dBi = \underline{\underline{50 dBW}}$$

b) flux density on receiving area:

$$W_f \overset{= (EIRP) \cdot L_a / 4 \pi R^2}{=} EIRP - 10 \log (4 \pi R^2)$$

$$= 50 - \overset{162,12}{\cancel{163,53}} dBWm^{-2}$$

$$= -112,12 \frac{dBW}{m^2}$$

$$W_f = \frac{P_t G_t}{4 \pi h^2}$$

$$EIRP = P_t G_t$$

5.4 Ground Station

a) EIRP of G.S.: $P_t \cdot G_t = \overset{\overset{30 dBW}{\shortparallel}}{10 \log (1000)} + G_t$

$$G_t = \left(\frac{4\pi}{\lambda^2}\right) A_{eff} = \left(\frac{4\pi}{\lambda^2}\right)\left(\frac{\pi D^2}{4} \eta\right) = \left(\frac{\pi D f}{c}\right)^2 \eta$$

$$= \left(\frac{\pi \cdot 4 \cdot 14 \cdot 10^9}{300 \cdot 10^6}\right)^2 \cdot 0,6 = 206340$$

$$\Rightarrow 10 \log 206340 = 53,146 dBi$$

$$EIRP = 30 dBW + 53,15 dBi = 83,15 dBW$$

↱ !! haakjes

b) $L_s = \left(\frac{\lambda}{4\pi h}\right)^2 = \left(\frac{c}{4\pi h f}\right)^2 = \left(\frac{300\cdot10^6}{4\pi\cdot36\cdot10^6\cdot14\cdot10^9}\right)^2 = 2{,}24\cdot10^{-21}$

$= -206{,}5\,dB$

A.2
p 7

c) received power at satellite

$C = W_f\cdot A_R = \frac{P L_\ell\cdot G_t\cdot L_a\cdot D_r^2\,\eta}{16\,S^2}$

$P_r' = EIRP + G_R + L_s = 83{,}15 + 40 - 206{,}5$

$= -83{,}35\,dBW$

$= 10^{-8{,}335}\,W$

$= 4{,}62\cdot10^{-9}\,W$

5.5 Uplink - and Downlink Budget

a) $\frac{E_B}{N_o} = \frac{C}{N_o R} = \frac{P L_\ell\, G_t\cdot L_s\cdot L_a\cdot G_R\, L_{pr} L_{r}}{\boxed{k}\cdot T_s\, R}$ = zie solutions formule

↳ Boltzmann cte

uplink : $P_t \to 100W \to 10\log 100 \to 20\,dBW$

$L_\ell \to$ — $\to$ — $\to -1\,dB$

$G_t \to \eta\left(\frac{\pi D}{\lambda}\right)^2 = \eta\left(\frac{\pi D f}{c}\right)^2 \to 0{,}55\left(\frac{\pi\cdot12\cdot18\cdot10^9}{300\cdot10^6}\right)$

$\to 64{,}5\,dB$

$L_s \to \left(\frac{c}{4\pi h f}\right)^2 \to \left(\frac{300\cdot10^6}{4\pi\cdot40\cdot10^6\cdot18\cdot10^9}\right)^2 \to -20\overset{9}{0},$

$L_a \to$ / $\to$ / $\to -0{,}5\,dB$

L_{edge} — $\to$ / $\to -3\,dB$

$G_{Rx} \to 2500 \to 10\log 2500 = 34\,dBi$

$T_s \to 290\,K \to -10\log 290 = -24{,}6\,dBK$

$k \to 228{,}6\,dBK/Ws$

$R \to 10\,Mbit/s \to -10\log 10^7 = -70\,dB$

$\frac{E_B}{N_o} = P + L_l + G_t + L_{pr} + L_s + L_a + G_r + L_r + 228{,}6 - 10\log T_s - 10\log R$

$= (20 - 1 + 64{,}5 - 209{,}6 - 0{,}5 - 3 + 34$ $- 10\log(-24{,}6)$ $- 10\log(-70)$

$= 38{,}4$

downlink: $\frac{E_B}{N_0} = P + L_\ell + G_t + L_{pr} + L_s + L_a + G_r + L_r + 228{,}6$

$- 10 \log T_s - 10 \log R$

$P_t G_t$ (EIRP) $= 23$ dBW

$L_a = -0{,}5$ dB

$L_\ell = -3$ dB

~~[illegible]~~ $T_s = -10 \log 100 = -20$ dBK

$G_r = 10^6 \rightarrow 10 \log 10^6 = 60$ dBi

$k = +228{,}6$ dBK/Ws

$R = -10 \log 10^7 = -70$ dB

$$L_s = \left(\frac{\lambda}{4\pi R_E}\right)^2 = \left(\frac{c}{4\pi R_e f}\right)^2 = 10 \log \left(\frac{300 \cdot 10^6}{4\pi \cdot 40 \cdot 10^6 \cdot 4 \cdot 10^9}\right)^2$$

~~$= -236{,}5$ dB~~ ??

$= -196{,}5$ dB

5.6 Noise Temperature

zie solutions

5.7 Influence of rain on link performance

a) aflezen uit grafiek pg 565 SMAD → ± 22 dB

b) zie solutions!

5.8 Data Handling, Telecom, Power & Economics

1) Data Handling dict. A1 pg 177

→ accuracy
m in %
n in # bits/sample

a) $f_s \geqslant 2{,}2\, f_m$ $m = \dfrac{100}{2^{n+1}}$

*

1 bit/sample → m = 25%
2 bit/s. → m = 12,5%
3 bit/sa → m = 6,25%
4 bit/sa → m = 3,125%
5 bit/sa → m = 1,5625%
6 bit/sa → m = 0,78125%
7 bit/sa → m = 0,3906
8 bit/sa → m = 0,1953
9 bit/sa → m = 0,0976
10 bit/sa → m = 0,0488
11 bit/sa → m = 0,0244
12 bit/sa → m = 0,0122
13 bit/sa → m = 0,006

* temp: m = 1% → 6 bits needed
$10 \times 10 \times 6 = 600$ bits/s

* volt: m = 0,1% → 9 bits needed
$10 \times 1 \times 9 = 90$ bits/s

* experim: m = 0,01% → 13 bits needed
$f_s \geqslant 2{,}2 \cdot 200 = 440$ samples/s

⇒ $13 \cdot 440 = 5720$ bits/s

* total data required is $600 + 90 + 5720 = 6410$ bits/s

b) staat zn oplossing ~~bij~~ !! ⇒ 6410 Hz

2) Telecommunication (zie solutions)

a) zie solutions ; $\frac{E_b}{N_0}$ for 10^{-5} (BER) = 9,6 (SMAD pg 83)

b) figure 13-9, pg 561 SMAD

$\frac{E_b}{N_0} = 11,2$ dB (BER $\leq 10^{-7}$)

c) $\frac{E_b}{N_0} = 5,8$ dB

! coding gain = 11,2 − 5,8 = 5,4 dB

d) 2 × 6410 = 12820 bits/s

f) 5,4 dB → factor = 3,64 (= $10^{0,54}$)

$\Rightarrow \frac{30 \text{ W}}{3,64} = 8,24$ W RF transmission power

g) solution

3) Power System

a) saving of 33W saves 3,3 kg in mass for power system
(10 W/kg spec. power to mass ratio)

b) total mass saved → 1,8 + 3,3 ≃ 5 kg

4) Economics

kg year $geld
5 × 10 × 50000 = $ 2.500.000

5.9 Link Budget Exercise

a) solutions : (BPSK and BER $\leq 10^{-4}$)

b) $k = 1,381 \cdot 10^{-23}$

c)

d)

5.10 Uplink budget Exercise

Solution book

a) $EIRP = P_t G_t$

$$G_t = \eta \left(\frac{\pi D_t f}{c} \right)^2$$

b)

c)

d)

5.11 Telecommunication System

Hoofdstuk 1 : Structures

1.1 Random Loads

$$PSD = \frac{grms^2}{\text{width band}}$$

$$PSD \cdot 500\,Hz = (10\,g)^2 \Leftrightarrow PSD = \frac{100}{500}\,\frac{g^2}{Hz} = \frac{1}{5}\,\frac{g^2}{Hz} = 0{,}2\,\frac{g^2}{Hz}$$

1.2 Natural Frequency

$$35\,Hz \leq f = \frac{1}{2\pi}\sqrt{\frac{AE}{mL}}$$

$$\Leftrightarrow (35\,Hz)^2 \leq \left(\frac{1}{2\pi}\right)^2 \frac{AE}{mL}$$

$$\Leftrightarrow A \geqslant \frac{35^2 \cdot 250 \cdot 4\pi^2 \cdot 5}{70 \cdot 10^9}$$

$$\Leftrightarrow A \geqslant 0{,}0008636\ m^2$$

$$t = \frac{A}{2\pi r} \Rightarrow t \geqslant \frac{0{,}0008636\ m^2}{2\pi\ 0{,}5\ m} = 0{,}0002749\ m$$

$$\underline{\underline{= 0{,}2749\ mm}}$$

1.3 Tensile Strength

① Design loads

$X : m \cdot QSL \cdot j$

② cross-area & second moment of area I

$A = 2\pi r t$

$I = \pi r^3 t$

③ $$\sigma_{max} = \frac{g_y \cdot M \cdot L \cdot c}{I} + \frac{g_x \, M}{A} \leq \sigma_{allow}.$$

1.4 Margin of Safety

Pg 26

$$M.S = \frac{\sigma_{allow}}{j \cdot \sigma_{analysis - designload}} - 1$$

[illegible]

$1{,}5 \leq MoS \leq \infty$: easily improved!!

1.5

1.6 Launch & shock load

⇒ primary structure designed for QSL

1.7 Solar Array

$$f = \frac{0{,}56}{2\pi}\sqrt{\frac{EI}{mL^4}}$$

① $A = L \cdot b \Rightarrow b$

② $m = 0{,}8\,b = \dots \Rightarrow m$

③ $EI \geq \frac{0{,}1^2 \cdot 4\pi}{0{,}56^2} \cdot 0{,}4 \cdot 8^4 = 2062{,}5\,\mathrm{Nm}^2$

④ $I = \frac{1}{2} h^2 t\, b$

⑤ $I = \frac{EI}{E} = \dots$

⑥ $h = \sqrt{\frac{2I}{t\,b}}$

Hoofdstuk 2: Thermal Control

2.1 Earth Flux Density

$5{,}67 \cdot 10^{-8}$

$$\phi = \frac{E_{tot}}{4\pi D^2} = \frac{4\pi R^2 \sigma T^4}{4\pi D^2}$$

2.2 Absorption / Emission

SMAD 434 figuur

2.3 Heat Balance

$$Q_{in} = Q_{out}$$

$$\alpha A S + \text{dissipation} = \varepsilon A \sigma T^4$$

2.4 Heater System Sizing

1opp berekenen, 2 radiators

$$\Rightarrow \alpha S A + Q = \textcircled{2} \varepsilon A \sigma T^4$$

2.5 Conductive Network

↗

NIET KENNEN

2.6 Conductions

$$C_{ij} = \frac{kA}{L}$$

$$Q_{ij} = C_{ij} (T_i - T_j)$$

!! 2.7 Thermal Shoe Conduction

serie : $\frac{1}{C_{12}} = \frac{1}{C_1} + \frac{1}{C_2}$

parallel : $C_{12} = C_1 + C_2$

!! 2.8 Transient Behavior

$$Q_{in} - Q_{out} = \Delta Q = m \, C_p \frac{\Delta T}{\Delta t}$$

$\Rightarrow \Delta T$

!! 2.9 Power Source Elimination

2.10 Thermal Network

2.11 Iridium Thermal Design

Hoofdstuk 3 : Attitude & Control System

3.1 General :

A1 pg $\boxed{62}$ - $\boxed{68}$

3.2 3-Axis stabilisation

A 1 a) pg 71
b) 97 - 98

$K_p > 0$ & $K_d > 0$ → stable

3.3 Gravity Gradient Stabilisation

a) stable orientation in its orbit

zie SCHRIFT

b) calculations of the stability

zie SCHRIFT

3.4 Actuator Design : Reaction Wheels

a) max disturbance torque on S/C

Pg 85 (A1)

b) slew torque → slew manouver in 600s

Hoofdstuk 4 : Power System

4.1 Energy Source

zie 6.6.1 Solar Flux : idem!

4.2 Solar Array Sizing

* Array Power

$$P_{SA} = \frac{P_e \cdot T_e / X_e + P_d \cdot T_d / X_d}{T_d}$$

X_e / X_d $\boxed{\text{A1, pg 126}}$

* Life Degradation Factor $\boxed{\text{pg 129}}$

$$L_d = (1-\delta)^x$$

* Array Size

$$A_{SA} = \frac{P_{SA}}{P_{EOL}}$$

$P_0 = .$

$P_{BOL} = 0{,}77 \cdot P_0$

$P_{EOL} = P_{BOL} \cdot L_d$

$N = n \cdot \textcircled{m}$, number of strings

* number of cells in series

$$n = \frac{V_{SA}}{V_{cell}}$$

* m cell in strings

$$\frac{P_{sa}}{V_{sa}} = I_{SA} = m \, I_{cell}$$

4.3 Battery Sizing

Average Power delivered by battery

P_{bat}

V_{bat}

Peak current (discharge current (I_d))

$$I_d = \frac{P_e}{V_{bus}}$$

Nr of battery cells

$$N_{bat} = \frac{V_{bat}}{\ldots}$$

nr eclipse periods

DoD

REST ZIE SCHRIFT

Hoofdstuk 5 : Telecommand and Telecommunication

5.1 Decibels

5.1.1 dB

$\frac{E_b}{N_0} = \frac{100}{1} \Rightarrow$ decibels: $10 \log_{10}(100) = \underline{\underline{20\ dB}}$

5.1.2 dBi

$$\left.\begin{array}{l} G = 100 \\ P = 100\,W \end{array}\right\} \Rightarrow 10 \log_{10} G = 10 \log_{10} \frac{P_{ant.}}{P_{isot}} = 10 \log \left(\frac{P G / 4\pi}{P / 4\pi r} \right.$$

$\Rightarrow 10 \log G = 10 \log_{10} 100 = \underline{\underline{20\ dBi}}$

5.1.3 dBW and dBm

$P_A = 1000\,W \Rightarrow 10 \log_{10} 1000 = \underline{\underline{30\ dBW}}$

$\Rightarrow 10 \log_{10} \frac{1000}{\boxed{0{,}001}} = \underline{\underline{60\ dBm}}$

?

5.2 Free Space Loss for a GEO s/c

for C, X, Ku, K & Ka band

$h = 36000$ km

C band : $f = 4 - 8\ GHz)$

$$L_{FS} = \left(\frac{\lambda}{4\pi h} \right)^2 = \left(\frac{c}{4\pi h f} \right)^2 = \left(\frac{300 \cdot 10^6}{4\pi \cdot 36 \cdot 10^6 \cdot \boxed{4} \cdot 10^9} \right)^2$$

$\Rightarrow 10 \log_{10} (A_{ns}) = \underline{\underline{-195{,}6\ dB}}$ tot $\underline{\underline{-201{,}6\ dB}}$

zelfde voor X, Ku, K & Ka band $\boxed{B,\ pg\ 72}$

5.3 EIRP & FLUX DENSITY

a) EIRP $= P_t \cdot G_t$

$G_t = 30\,\text{dBi}$

$P_t = 10 \log 100 = 20\,\text{dBW}$

$\Rightarrow \text{EIRP} = 30 + 20 = 50\,\text{dBW}$

b) flux density on the receiving area

$$W_f = \frac{P_t \cdot G_t}{4\pi h^2} \quad \left[\frac{W}{m^2}\right]$$

$$\Rightarrow W_f = \text{EIRP} - 10 \log_{10}(4\pi h^2)$$

$= 50\,\text{dBW} -$ ~~[illegible]~~ $\overset{\wedge}{}$ $162,1$ $\text{dB}\,m^{-2}$

~~$= -52,1\,\text{dBW}\,m^{-2}$~~

$= 112,1\,\text{dBW}\,m^{-2}$

5.4 Ground Station

a) EIRP of GS $= P_t \cdot G_t = 30\,\text{dBW} + 53,1\,\text{dBi}$

$P_t = 10 \log 1000 = 30\,\text{dBW}.$

$= \underline{\underline{83,1\,\text{dBW}}}$

$$G_t = \left(\frac{4\pi}{\lambda^2}\right) A_{eff} = \left(\frac{4\pi}{\lambda^2}\right)\left(\frac{\pi D^2}{4}\eta\right) = \eta\left(\frac{\pi D f}{c}\right)^2$$

$$= 0,6\left(\frac{\pi \cdot 4 \cdot 14 \cdot 10^9}{300 \cdot 10^6}\right)^2 = \underline{\underline{53,1\,\text{dBi}}}$$

5.5 Uplink - and Downlink Budget

uplink $\frac{E_b}{N_0} = \boxed{35,4}$

$P_t = 100\,W = 10 \log_{10} 100 = \boxed{20\,dBW}$

$L_\ell =$ (feeder loss) $= \boxed{1\,dB}$

$G_t = \eta \left(\frac{\pi D f}{c} \right)^2 = 0,55 \left(\frac{\pi \cdot 12 \cdot 18 \cdot 10^9}{300 \cdot 10^6} \right)^2$

$= \boxed{64,5\,dB}$

$L_s = \left(\frac{c}{4 \pi h f} \right)^2 = 10 \log \left(\frac{300 \cdot 10^9}{4\pi \cdot 40 \cdot 10^6 \cdot 18 \cdot 10^9} \right)^2 = \boxed{-209,6 d}$

$L_a = \boxed{-0,5\,dB}$

$L_{pr} = \boxed{-3\,dB}$

$G_r = 2500 = 10 \log_{10} 2500 = \boxed{34\,dBi}$

$L_{edge} = \boxed{-3\,dB}$

k = Boltzman cte $\Rightarrow 10 \log k = \underline{\underline{+228,6}}\ \frac{dBW}{Hz \cdot K}$

$T_0 \Rightarrow -10 \log 290 = \underline{\underline{-24,6\,dBK}}$

$R \Rightarrow -10 \log 10^7 = \underline{\underline{-70\,dBi}}$

optellen geeft : $\boxed{35,4\,dB}$

Downlink :

$$\frac{E_b}{N_0} = \boxed{\underline{\underline{24{,}6\ dB}}}$$

$EIRP = \underline{\underline{23\ dBW}} = P_t \cdot G_t$

$L_l = 0$

$$L_s = 10\log\left(\frac{300^6}{4\pi \cdot 40 \cdot 10^6 \cdot 4 \cdot 10^3}\right)^2 = \underline{\underline{-196{,}5\ dB}}$$

$L_a = \underline{\underline{-0{,}5\ dB}}$

$L_{pr} = 0$

$G_r = 10 \log_{10} 10^6 = \underline{\underline{60\ dBi}}$

$T_s : -10 \log 100 = \underline{\underline{-20\ dBK}}$

Boltzman : $-10 \log k = +\underline{\underline{228{,}6}}\ \frac{dBK}{Ws}$

$R : -10 \log 10^7 = \underline{\underline{-70}}\ dB$

b.) L_{FS} :

$$L_{FS} = \left(\frac{\lambda}{4\pi h}\right)^2 = \left(\frac{c}{[4\pi h f]}\right)^2 = \dots = -206{,}4\,\mathrm{dB}$$

c) $P_{received} = EIRP + G_r + L_{FS}$

$= 83{,}1\,\mathrm{dBW} + 40\,\mathrm{dBi} - 206{,}4\,\mathrm{dB}$

$= -83{,}3\,\mathrm{dBW}$

$\Longrightarrow 10^{-8{,}33} = \underline{\underline{4{,}67 \cdot 10^{-9}\,\mathrm{W}}}$

5.5 Uplink and Downlink Budget

a) calculate uplink budget $\frac{E_b}{N_0}$

$$\frac{E_b}{N_0} = \frac{C}{N_0 R} = \frac{P \cdot L_l \cdot G_t \cdot L_s \cdot L_a \cdot L_{pr} \cdot G_r \cdot L_r}{k \; T_s \; R}$$

$$\frac{E_b}{N_0} = P + L_l + G_t + L_{pr} + L_s + L_a + G_r + L_r$$

in dB

5.6

geen tentamenstof

5.7 Influence of Rain on Link Performance

$f = 30\ \text{GHz}$
$EIRP = 30\ \text{dBW}$
$G_{gs} = 50\ \text{dBi}$
$T_{sky} = 8\ K$
$T_{ground} = 20\ K$
$L_{FS} = 206\ dB$

elevation angle antenna : 10°
availability = 99,5%
$L_{RFX} = 0{,}5\ dB$
$T_{RFX} = 290\ K$

$T_{eRX} = 60\ K$

Gevraagd:

a) A_{rain}? aflezen grafiek p 585 $\Rightarrow$ $\underline{\underline{22\ dB}}$

b) noise temperature : clear sky →
rain condition

$T_{rain} = 290°\ K$

① $T_A = T_{sky} + T_{ground} = 28\ K$ in clear sky

② $$T_A = \frac{T_{sky}}{A_{rain}} + T_{rain}\left(1 - \frac{1}{A_{rain}}\right) + T_{ground}$$

$$= \frac{8}{10^{2,2}} + 290\left(1 - \frac{1}{10^{2,2}}\right) + 20$$

$$= \underline{308{,}2\ K}$$

GEEN

TENTAMENSTOF

① T_s under clear sky:

$$T_s = \frac{T_A}{L_{RFX}} + T_{RFX}\left(1 - \frac{1}{L_{RFX}}\right) + T_{eRX}$$

$$T_s = \frac{28}{10^{0,05}} + 290\left(1 - \frac{1}{10^{0,05}}\right) + 60$$

$$= \cancel{100,3}\ 116,5\ K$$

$$= \underline{20,7\ dBK}$$

② T_s under rain condition

$$T_s = \frac{T_A}{L_{RFX}} + T_{RFX}\left(1 - \frac{1}{L_{RFX}}\right) + T_{eRX}$$

$$= \frac{308,2}{10^{0,05}} + 290\left(1 - \frac{1}{10^{0,05}}\right) + 60$$

$$= 366,22\ K = 25,64\ dBK$$

$$L_{path|clear\ sky} = L_{FS}$$

$$L_{path|rain} = L_{FS} + A_{rain}$$

5.8 Data Handling, Telecom, Power & Economics

5.8.1

a) minimum data rate

$f_s \geq f_m \cdot 2,2$ $\qquad m = \frac{100}{2^{n+1}}$

bits tabel % accuracy

bits	% accuracy
0	50
1	25
2	12,5
3	6,25
4	3,125
5	1,5625
6	0,78125
7	0,390625
8	0,1953125
9	0,09765625
10	0,04883
11	0,0244
12	0,0122
13	0,0061
14	0,00305
15	0,0015
16	0,000763

T : 1% => 6 bits
10 x 10 signals => DR = 6 · 10 · 10 = 600 bits/s 1

V : 0,1% => 9 bits
10 x 1 signals => DR = 9 x 10 = 90 bits/s 2

Exp : 0,01% => 13 bits
200 Hz => 2.2 · 200 = 440 samples/s
=> 13 x 440 = 5720 bits/s 3

TOTAL = 1+2+3 = 6410 bits/s

b) ⇒ minimum bandwidth = 6410 Hz

5.8.2

a) BER $\leq 10^{-7}$

utilisation spectrum = 1 ⇒ 6410 Hz

b) minimal value of energy

K = 7 & R = 1/2

M E_b/N_0 = ~~11,2 dB~~ 5,8 dB

c) data rate needed

p561 2 bits for each data bit ⇒ 2 × 6410 bits/s
= 12 820 bits/s

d) Coding Gain = 11,2 − 5,8 = 5,4 dB

e) P_{RF}!

factor: $10^{0,94}$ = 3,64 ⇒ i.p.v 30 W ⇒ $\frac{30}{3,64}$ = 8,24 V

f) Power saved: 55 W − 21 W = 34 W

g) Mass saved: 5 − 3,2 = 1,8 kg

5.8.3 Power System

a) power / mass ratio = 10 W / kg

saving 34W saves 3,4 kg

b) 3,4 kg + 1,8 $\overset{= 5,2\,kg}{\approx}$ 5 kg

5.8.4 Economics

1 kg = $50000 / year.

time = 10 year

$\Rightarrow$ 5,2 · 10 $50 000 = $2,600 000

can be saved

5.9 Link Budget

SMAD 561

a) BPSK, BER 10^{-4} $\Big\} \xrightarrow{\text{tabel 13.9}}$ $\underline{\underline{8,4\,dB}}$

$$\Rightarrow \frac{E_b}{N_0} = 8,4\,dB \Rightarrow \text{ratio} = 10^{0,84} = 6,91$$

b) signal power at the input:

$$C = \text{input power} = E_b \cdot R_b$$

1) $N_0 = \textcircled{k}\, T_{eff} = 1,381 \cdot 10^{-23} \cdot 371 = 5,12 \cdot 10^{-21}\ Ws$

$\|$

Boltzmann cte $= 1,38 \cdot 10^{-23}\ J/°K$

$\boxed{\text{zie A2 pg 11}}$

2) $\dfrac{E_b}{N_0} = 6,91 \Rightarrow E_b = 6,91 \cdot 5,12 \cdot 10^{-21}$

$= 3,54 \cdot 10^{-20}\ Ws$

3) $R_b = 6,1$ (transmission rate)

$$\Rightarrow C = 3,54 \cdot 10^{-20} \cdot 6,1 \cdot 10^{6}$$

$$= \underline{\underline{2,16 \cdot 10^{-13}\ W}}$$

c) Gain receiver antenna:

~~$G_{ra} =$~~

$$C = P \cdot G_t \cdot G_r \left(\frac{\lambda}{4 \pi h} \right)^2 = P\, G_t\, G_r\, L_s$$

$$\Rightarrow G_r = \left(\frac{C}{P G_t} \right) \left(\frac{4 \pi h f}{c} \right)^2$$

$$= \left(\frac{2{,}46 \cdot 10^{-13}\,W}{20W \cdot 398{,}1} \right) \left(\frac{4 \cdot \pi \cdot 36 \cdot 10^{6} \cdot 12{,}2 \cdot 10^{9}}{300 \cdot 10^{6}} \right)^2$$

$$G_t = 26\,dB \Rightarrow 10^{2{,}6} = 398{,}1$$

$$= 9181{,}7$$

$$= \underline{\underline{39{,}6\,dB}}$$

B E R

d) effective receiver antenna area & D_{RA} with unaltered

$$G_t = 26\,dB \cong 398$$

$$\lambda = \frac{c}{f} = \frac{3 \cdot 10^8}{12{,}2 \cdot 10^9} = 2{,}46 \cdot 10^{-2}$$

$$\frac{\pi}{4} D^2$$

SMAD 559

13.7

$$G_r = \left(\frac{\pi D_r^2 \eta}{4} \right) \left(\frac{4\pi}{\lambda^2} \right) = \frac{\pi^2 D_r^2}{\lambda^2} \eta = A \eta \frac{4\pi}{\lambda^2}$$

$$\Rightarrow A = \frac{G_r \lambda^2}{\eta 4\pi} = \frac{9181{,}7 \cdot 2{,}46 \cdot 10^{-2}}{0{,}8 \cdot 4 \cdot \pi} = 0{,}56\,m^2$$

$$\Rightarrow D = \sqrt{\frac{4A}{\pi}} = 0{,}84\,m$$

5.10 Uplink Budget

a) EIRP

$EIRP = P_t G_t = 10 \lg 10000 + 10 \log$

$= 93{,}1 \, dBW$

$P_t = \text{geg}$

$G_t = \eta \left(\frac{\pi D f}{c} \right)^2$

b) $L_{FS} = \cancel{(4\pi S} \left(\frac{4\pi R}{\lambda} \right)^2$

$= \left(\frac{\lambda}{4\pi R} \right)^2 = \left(\frac{c}{4\pi R f} \right)^2$

c) minimum $\frac{E_b}{N_0}$ ratio

$C = E_b \boxed{R_b} = \rightarrow$ transmission rate

$N_0 = k T_{eff} = 1{,}381 \cdot 10^{-23} \cdot 290 = 4 \cdot 10^{-21}$

$E_b = \frac{2 \cdot 10^{-13} \, W}{10^7} = 2 \cdot 10^{-20} \, Ws$

$\Rightarrow \frac{E_b}{N_0} = 5 \Rightarrow 7 dB$

d) BER?

10^{-3} label 13.9 pg 561 SMAD

e) Antenna gain s/c

$$G_r = \left(\frac{\overset{\cancel{P_a}\ ,,\ \textcircled{C}\ \text{ges}}{\cancel{S}\, P_r}}{\underbrace{\textcircled{P_t}}_{\text{geg}}\ \underbrace{\textcircled{G_t}}_{\to \textcircled{a}}}\right)\left(\frac{4\pi l}{\lambda}\right)^2 = 426 \cdot 10^2$$

$\Rightarrow$ 46,3 dB

f) $A_{eff} = G_r \left(\frac{\lambda^2}{4\pi}\right) = 1{,}56\ m^2$

$\Rightarrow$ real area $= \frac{1{,}56\ m^2}{0{,}6} = 1{,}82\ m$

5.11 Telecommunications System

P_r ?

$\Rightarrow$ ① $EIRP = P_t\, G_t = 7{,}8\,dBW + 24{,}3\,dBi$

$= 32{,}1\,dB$

② $L_{FS} = \left(\dfrac{c}{4\pi h f}\right)^2 = -149\ 7\,dB$

③ $G_r = \left(\dfrac{\pi D f}{c}\right)^2 = 4{,}5\,dB$

④ $P_r = 32{,}1 - \underbrace{154}_{L_{FS@800km}} + 4{,}5 = -112{,}4 = \underline{\underline{5{,}75 \cdot 10}}$

* Hoofdstuk 6 : Propulsion

Tsiolkovsky : $\Delta V = w \ln \left(\frac{M_0}{M_e} \right)$

A2, pg 54 : mass ratio

$\rightarrow$ exhaust mass flow

Rocket thrust : $F = m \cdot w$

$t = \frac{M_p}{m} \Rightarrow m = M_p / t$ with $M_p = M_0 - M_e$

● or simply $m = \frac{F}{w}$

specific impulse $(I_{sp})_{sys} = \frac{F \cdot t}{M_p \cdot g_0} = I_{sp}$

$$= \frac{m w t}{m t \cdot g_0} \overset{cte\ m}{=} \boxed{\frac{w}{g_0} = I_{sp}}$$

● Power need $P_{jn} = P_j / \eta$

$$P_j = 1/2\, m w^2 = \frac{1}{2} F w$$

Chemical Rockets:

$F = m \cdot v_e + (p_e - p_a) \cdot A_e$ ⓞⓡ $F = m w$

with $w = v_e + (p_e - p_a) \frac{A_e}{m}$

+ ideal exhaust velocity

$$V_e = \sqrt{\frac{2\gamma}{\gamma-1}\,\frac{R_A\,T_c}{M}\left[1-\left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} = \overset{\text{cte}}{\overset{\|}{K}}\cdot\sqrt{\frac{T_c}{M}}$$

γ = specific heat ratio

R_A = absolute gas cte = 8314,32 J/kg-mol/K

T_c = temperature in the combustion chamber

M : molecular weight (2 - 30 kg/mol)

p_e/p_e = pressure ratio $\frac{\text{nozzle}}{\text{reaction chamber}}$ (0,5 - 0,004)

$$\boxed{\frac{p_e}{p_c}\ \text{tabel}}$$

$p_e < p_a \Rightarrow$ over expanded $\Rightarrow$ energy loss

$p_e = p_a \Rightarrow$ ideally expanded

$p_e > p_a \Rightarrow$ under expanded $\Rightarrow$ not all energy can be used.

mass flow, $m = \frac{p_c\,A_T}{c^*}$

$$F = F_{vac} - p_a\,A_e$$

$\hookrightarrow p_a \downarrow$ with $h\uparrow$

$\Rightarrow \left.\begin{array}{l} F\uparrow \\ I_{sp} \end{array}\right)$ met $h\uparrow$

typical I_{sp} <u>pg 68</u>

limitations to the performance p69
- chamber pressure
- chamber temperature
- available chemical propellants
- motor size (diameter s/c)

Non-chemical:
- Resistojet : electrical heater (T = 2500 - 3000K)
- Arcjet : electric arc discharge (T ↑)
- Thermo-nuclear engine : nuclear reactor to heat propellant
- Solar thermal propulsion : solar energy → high T gas
- Laser propulsion

Exhaust Velocity:

$$w \propto \sqrt{\frac{T}{M}}$$

heat up mass flow of propellant to high T

Thermal power : $P_{heat} = \dot{m}\, c_p \Delta T$

- Electric thrusters
  - electrostatic
  - magneto-plasma-dynamic (MPD)
  - ion thrusters → voltage difference (large!!)

$$\hookrightarrow w = \sqrt{\frac{2q\,\boxed{\Delta V}}{\boxed{m_q}}} \quad \text{— voltage diff.} \qquad \longrightarrow m_q = \frac{\hat{M}}{N_A} \quad - 6 \cdot 10^{23}$$

q = electric charge

$\hat{M}$ = molecular weight $\boxed{p\ 81}$

Beam current

typical thermal thruster performances

→ pg 85-86

Feed system : pumps vs. tank pressurization

pg 93 → advantages

→ disadvantages

blow-down vs. regulated

Hoofdstuk 6: Propulsion

A2

6.1 Requirements

① space propulsion: a class of propulsion that allows to produce a propulsive force in (empty) space. It excludes e.g. those means of propulsion that

A2 p43 → require the ingestion of the surrounding air to provide the propulsive force, like air-breathing jet engines and piston engines

→ generate the propulsive force through direct contact with, like wheeled or tracked propulsio

② typical propulsive functions:

a) orbit changes:
- ascent flight, orbit injection, de-orbit, ...
- plane changes

A2 p43 b) orbit stabilization or "station keeping" to compensate for effect of disturbing forces: drag, solar wind,

c) attitude control to change the attitude of the s/c or to compensate for disturbing forces

d) others: spin-up/down, unloading of reaction or momentum wheels, separation of stages, propellant settling, ...

③ Requirements for a propulsion subsystem (thrust + thrust duration)
- configuration requirements
- p 45 life, reliability, availability, maintainability, safety re-usability, degree of autonomy, ...
- constraints with respect to mass, volume, cost, loads, date in use, electrical power requirement, environmental lo

④ $M = 1000\,kg = cte$
$\Delta V = 10 km/s$

calculate : the total impulse, I

opl : $I = M \cdot \Delta V = 1000\,kg \cdot 10\,000\ m/s$
$= 10$ miljoen Ns

⑤ mass decreases linearly (constant mass flow rate) from 1500 kg to 1000 kg with increasing velocity

pg 44

calculate : F_{max} $(a_{max} \leq 10\, g_0)$

$$I = \int M(v)\, dv$$

$$M(v) = M_0 - \frac{M - M_e}{V_e - V_0}(V - V_0) = 1500 - \frac{500}{10^4}(V - V_0)$$

$$\Rightarrow I = \int_0^{10^4} \left(1500 - 0{,}05\,(V - V_0)\right) d(v - v_0)$$

$$= 1500\,(V - V_0) - \frac{0{,}05\,(V - V_0)^2}{2} \Bigg|_0^{10^4}$$

$$= 1{,}25 \cdot 10^7\ Ns$$

⑤ vgl ④ : increasing total impulse with decreasing mass

pg 53
⑤

⑥ max thrust F

$F_0 = 1500 \cdot 10 g = 147{,}15 \cdot 10^3$ kN
$F_e = 1000 \cdot 10 g = 98{,}1 \cdot 10^3$ kN

→ thrust varies $I = \int_0^{t_a} F \, dt$ (pg 52)

⑦ minimum thrust duration

$$t_{min} = \frac{\Delta v}{a} \Rightarrow t_{min} = \frac{10^4}{10 \cdot 9{,}80665} \approx 101{,}97 \text{ s}$$

pg 53 $\dot{m} = \frac{F}{w} = ~~[illegible]~~ \frac{98{,}1 \cdot 10^3}{10000} \cdot \ln\left(\frac{1500}{1000}\right) = 3{,}98 [kg/s] \Rightarrow t = \frac{M_p}{\dot{m}} = \frac{500}{3{,}98} = 125{,}7$

⑧ spin up maneuver
0 → 60 rpm in 10 s
moment arm r = 2 m
cylindrical shape, uniform mass distr., constant ω

$$H_{O_2} - H_{O_1} = F \cdot r \cdot t$$

with $H_O = I_O \cdot \omega_*$ ⟹ $H_{O_1} = 0$ since $\omega_1 = 0$

$$I_O = \frac{1}{2} M r^2 = \frac{1}{2} 1000 \cdot 2^2 = 2000 \text{ kg} \cdot \text{m}^2$$

$$F = \frac{I_O \omega}{r t} = \frac{2000 \cdot 1 \cdot 2\pi}{2 \cdot 10} = 628{,}3 \text{ N}$$

⑨ s/c: m = 1000 kg @ 400 km

?

a) drag makeup continuous
b) " " only 5% of the orbital period

v = 7,669 km/s {orbit period: 92,56 min
a)

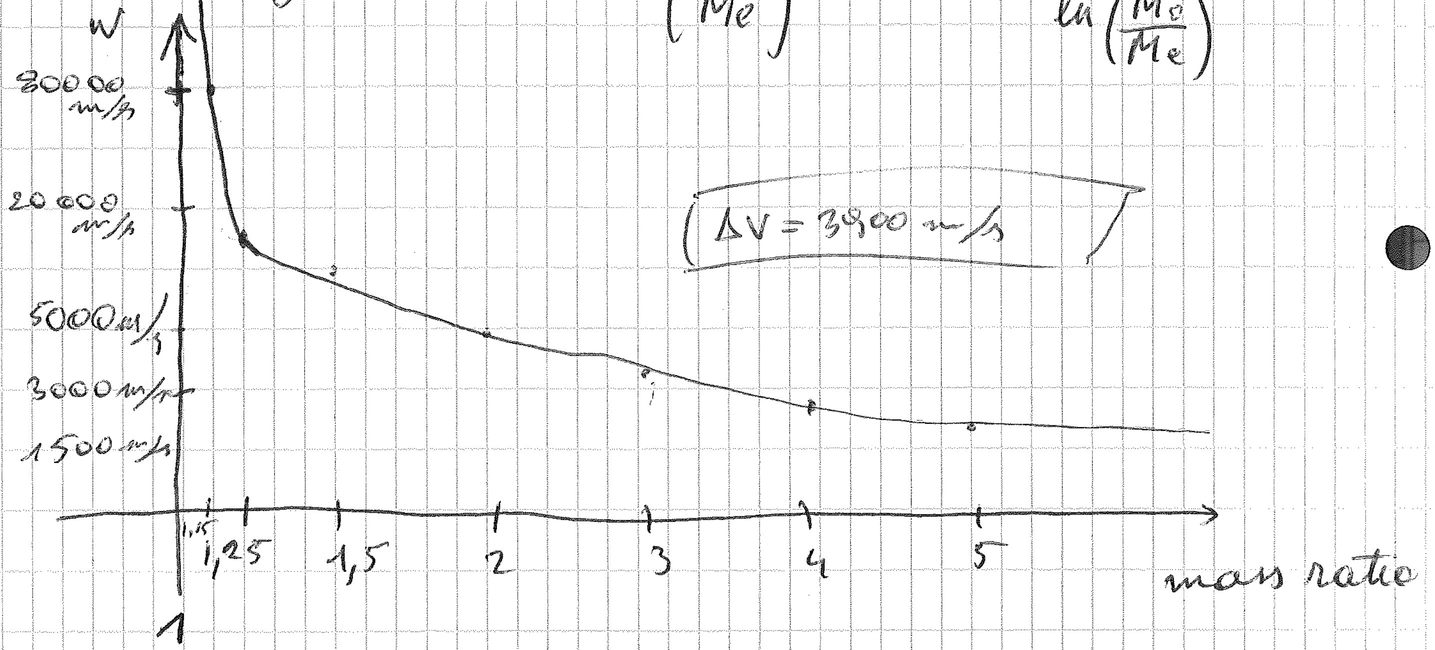
6.2 Rocket Fundamentals

① moon mission

$\Delta V = 3,9$ km/s

mass-ratio vs. effective exhaust velocity

Tsiolkovsky : $\Delta V = w \ln\left(\frac{M_0}{M_e}\right) \Rightarrow w = \frac{\Delta V}{\ln\left(\frac{M_0}{M_e}\right)}$



② upper stage (perigee kick) : LEO → GEO

$a_{max} = 1 g_0$

$\Delta V = 3,94$ km/s

$w = 3000$ m/s

dry mass $m = 1100$ kg

gevr: M_p , F_{max} , t_{min}

opl: a) **M_p**: $\Delta V = w \ln \frac{M_0}{M_e} \Rightarrow M_0 = M_e\, e^{\frac{\Delta V}{w}}$

$\Rightarrow M_0 = 1100 \text{ kg} \cdot e^{\frac{3940}{3000}} = 4090,4$ m/s

$M_p = M_0 - M_e = \underline{\underline{2990,4 \text{ kg}}}$

b) $F = cte$: $F = 1100 \text{ kg} \cdot 9,81 = 10,8$ kN

$F = var$: $F = 4090 \text{ kg} \cdot 9,81 = 40,1$ kN

c) $\dot{m} = \frac{F}{w} = \frac{10,8 \cdot 10^3}{3000} = 3,6 \left[\text{kg/s}\right] \Rightarrow t_d = \frac{2990}{3,60} = 830,6$ s

c) F = [illegible] var $\quad t = \frac{3900\ m/s}{9,80665\ m/s^2} = \frac{\Delta v}{a} = 401,8\ s$

③ total propellant mass:

* secondary system:

$I_{sp} = 150\ s$

$I_{sp} = \frac{w}{g_0} \Rightarrow w = 1500\ m/s$

$M_0 = 100\ kg \cdot e^{\frac{70}{1500}} = 104,8\ kg$

* primary system:

with $I_{sp} = \frac{w}{g_0} \Rightarrow w = 300\ s \cdot 10\ m/s^2 = 3000\ m/s$

$\Delta V = 250\ m/s + 75\ m/s = 325\ m/s$ ($1^e + 2^e$ maan.)

$M_e = 104,8\ kg$

$\Rightarrow M_0 = M_e\ e^{\frac{\Delta V}{w}} = 104,8\ kg \cdot e^{\frac{325\ m/s}{3000\ m/s}} = \underline{\underline{116,8\ kg}}$

$M_p = M_0 - M_e = 116,8 - 100\ kg = \underline{16,8\ kg}$

($M_{p,\text{secondary}} = 4,8\ kg$; $M_{p,\text{primary}} = 12\ kg$)

6.3 Chemical Rockets

6.3.1 Propellant Properties

liquid oxygen and kerosene → mixture ratio 2,25

gevr: flame temperature, molar mass, specific heat ratio & characteristic velocity

opl: $\boxed{\text{webpages}}$

mix	T	Molar mass	sp. heat rat.	char. v. (m/s)
2,2	3313,5	21,4	1,139	1781,9
2,3	3349,3	21,8	1,134	1777,3

⇒ gemiddelde nemen

6.3.2 Chemical Rocket Analysis

gevr:
a) nozzle pressure ratio
b) exhaust velocity
c) throat ~~velocity~~ area
d) mass flow
e) pressure in nozzle exit
f) nozzle exit area
g) vacuum thrust

opl: a) $F = 2{,}5\,kN$
$w = 3000\,m/s$
$\gamma = 1{,}3$
geom. expansion ratio: 100

pg 65
16, figuur

$$\Rightarrow \frac{p_e}{p_c} \overset{\text{figuur}}{\cong} 2500$$

pg 63

b) $$V_e = \sqrt{\frac{2\gamma}{\gamma-1}\,\frac{R_A T_c}{M}\left[1-\frac{p_e}{p_c}\right]^{\frac{\gamma-1}{\gamma}}} = \sqrt{\frac{2\cdot 1{,}3}{0{,}3}\,\frac{8314{,}32\,(2473{,}15)}{20}\,*}$$

$$* \; \overline{1 - 2500^{\frac{0{,}3}{1{,}3}}}$$

$$= 2605{,}2\,m/s$$

c) area ratio : 100 $A? \rightarrow d_t = 5\,cm$

$\Rightarrow$ diameter ratio : 10

$d_N = 5 \cdot 10\,cm \rightarrow \boxed{A_{Nt} = \frac{\pi}{4}(0,5)^2 = 0,196\,m^2}$

$A_{th} = \frac{\pi}{4}(5 \cdot 10^{-2})^2 = 0,00196\,m^2$

d) mass flow $\dot{m} = \frac{p_c \cdot A_t}{c^*} = \frac{10 \cdot 10^5 \cdot 0,196}{2240} = 87,66\,\frac{kg}{s}$

e) p_{Ne} ? $\frac{p_e}{p_c} = \frac{1}{2500}$; $p_c = 10\,bar = 10 \cdot 10^5\,Pa$

$\Rightarrow p_e = \frac{10^6}{2500} = 400\,Pa = 400\,\frac{N}{m^2}$

f) nozzle exit area

$\boxed{!?}$

A_{Ne} ? $A_t \cdot 100 = \cancel{0,196\,m^2}\ \underline{0,196\,m^2}$

g) $F_{vac} = \dot{m} \cdot w = \dot{m}\left(v_e + \left(p_e - \underset{0}{p_a}\right)\frac{A_e}{\dot{m}}\right) = \dot{m} v_e + (p_e - p_a)A_e$

$= 87,66\,\frac{kg}{s} \cdot 2785,6\,m/s + 400\,\frac{N}{m^2}(0,196\,m^2)$

$= \underline{\underline{2471\,N}}$

requirements not totally achieved. 2471N ipv 2500N

6.3.3 Effect of Design Parameters

ⓐ ① $F = \dot{m} w = \dot{m} v_e + (p_e - p_a) A_e$

$$\dot{m} = \frac{p_c \quad A_t}{c^*} = \frac{20 \cdot 10^5 \cdot 0{,}00196}{2240} = 1{,}75 \frac{kg}{s}$$

$$F = 1{,}75 \frac{kg}{s} \cdot 2785{,}6 \ m/s \underset{\uparrow}{+} 800 \ Pa \cdot 0{,}196 = \underline{\underline{5031{,}6 N}}$$

$5031{,}6 -$

$\Delta F = 2471 \quad = \underline{\underline{2560 N}}$

ratio = 100 ! $p_e = \frac{20 \cdot 10^5}{2500} = 800 \frac{N}{m^2}$

$\Longrightarrow I_{sp} = \frac{w}{g_0} = \frac{2875{,}2}{9{,}80665} = 293{,}2 s$

② $T = 3000 K$, $c^* = 2467 \ m/s$

$\Longrightarrow V_e = \dots = \underline{\underline{3005 \ m/s}}$

$\dot{m} = \frac{P_c \cdot A_t}{c^*} = \dots = 0{,}79 \frac{kg}{s}$

$\Longrightarrow F = 0{,}79 \cdot 3005 + 400 \cdot 0{,}196 = 2466 N$

$I_{sp} = \frac{w}{g_0} = \frac{F}{\dot{m} \cdot g_0} = 318{,}3 s$

b) $F = cte$ $\quad p_c = 20 \cdot 10^5 \ Pa$

$\dot{m} = cte$

$D_{th} = \sqrt{\frac{4}{\pi} \frac{0{,}00196}{2}}$

$D_e = \sqrt{\frac{4}{\pi} \cdot \frac{0{,}196}{2}}$

$= \underline{\underline{0{,}353 m}}$

gevr: A_{n_e}?

$\Longrightarrow p_e = 800 N/m^2$

$\Longrightarrow$ ~~At~~ 2 $p \Rightarrow 2\dot{m}$, maar $\dot{m} = cte$

$\Longrightarrow A_t^* = \frac{A_t}{2}$ $\Longrightarrow$ ~~Dthl ≠ $A_N = \frac{\pi}{8}(0{,}5)^2 = 0{,}098$~~

6.3.4 Chemical Rocket Design

a) ① mass flow :

$$\dot m_{req.} = \frac{F}{W} = \frac{400}{3000} = ,1333$$

② $$\dot m = \frac{p_c \cdot A_t}{c^*} \Rightarrow A_t = \frac{0,13333 \cdot \boxed{1675}}{20 \cdot 10^5} = 0,000111666 \text{ m}$$

→ web pages

$$= 1,116 \cdot 10^{-4} \text{ m}^2$$

③ $v_e = ?$

web-page : $\begin{cases} \gamma = 1,23 \\ M = 17,4 \end{cases}$

$\boxed{\text{figure}}$ $$\frac{p_e}{p_c} = \frac{1}{600}$$

$$\Rightarrow v_e \overset{\text{invullen}}{=} \dots = 2985,5 \text{ m/s}$$

④ $$F = \cancel{\dot m v_e} + (p_e - \underset{=0}{\cancel{p_a}})A_e = \frac{20 \cdot 10^5}{600} \cdot 50 \cdot 1,116 \cdot 10^{-4}$$

$$= \underline{\underline{18,61 \text{ N}}}$$

⑤ effective exhaust velocity

$$W = \frac{F}{\dot m} = \frac{(0,133 \cdot 2585,5 + 18,61)}{0,133} = \underline{\underline{3125}} \text{ m/s}$$

b) geen idee !

6.3.5 Effect of Altitude:

$\dot{m} \Rightarrow w = I_{sp} \cdot g_0$ & $\dot{m} w$

$\Rightarrow \dot{m} = \frac{500 \cdot 10^3}{400 \cdot 9{,}81} = 127{,}46$ kg/s

thrust in vac. $= w_{vac} - \frac{p_a A_e}{\dot{m}}$

zie schrift

$\dots \Rightarrow I_{sp} = (I_{sp})_{vac} - \frac{p_a A_e}{g_0 \dot{m}} = \underline{160\ s}$

$\Rightarrow F = F_{vac} - p_a A_e = \underline{\underline{200\ kN}}$

6.4 Alternative Rocket Propulsion

6.4.1 Thermal Power

$c_p = 14\,400 \ J/kg/K$

every second 0,34 g of hydrogen to T = 2500 K

$$* \ P = \dot{m} \cdot c_p \cdot \Delta T = 0{,}34 \cdot 10^{-3} \cdot 14400 \cdot 2500$$
$$= 12{,}240 \ kW$$

6.4.2 Thermal Rocket Design

geg: $F_{vac} = 16 \ kN$

$I_{sp,vac} = 850 \ s$

$D_{max} = 0{,}3$

Hydrogen: $\rightarrow c^* = 2175 \ m/s$

molar mass: 2 kg/kmol

$\lambda = 1{,}4$

$T = 2500 \ K$

$p_c = 10 \cdot 10^5 \ \frac{N}{m^2}$

ges: mass flow:

$$\Rightarrow \dot{m} = \frac{F}{W} = \frac{F}{I_{sp} \cdot g_0} = \frac{16000}{850 \cdot 9{,}80665} = 1{,}92 \ kg/s$$

(Jet) Beam Power: $P_j = \frac{1}{2} \dot{m} w^2 = \frac{1}{2} F W = \frac{1}{2} 16000 \ (850 \cdot 9{,}81)$

$$= 66{,}7 \ [MWatt]$$

Throat diameter: $\dot{m} = \frac{p_c \cdot A_t}{c^*} \Leftrightarrow A_t = \frac{\dot{m} \, c^*}{p_c} = \frac{1{,}92 \cdot 2175}{10^6}$

$$= 0{,}004176 \ m^2$$

$$\Leftrightarrow A_t = \frac{\pi}{4} (D_t)^2 \Leftrightarrow \sqrt{\frac{4 \cdot A_t}{\pi}} = D_t = \underline{\underline{0{,}073 \ m^2}}$$

* maximum allowable (geometric) expansion ratio

geg: max diameter = 0,3 m
diameter throat = 0,073 m

Diameter ratio = 4,11

$$\Rightarrow \text{expansion ratio} = \frac{A_e}{A_t} = \frac{\cancel{\frac{\pi}{4}}(0,3)^2}{\cancel{\frac{\pi}{4}}(0,073)^2} = \underline{\underline{16,89}}$$

* nozzle pressure ratio:

A2, figuur met expansion ratio = 16,89

⟹ rond 300 (pressure ratio)

* true exhaust velocity

$$V_e = \sqrt{\frac{2\gamma}{\gamma-1}\,\frac{R_A\,T_c}{M}\left[1-\left(\frac{P_c}{P_e}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

$$= \sqrt{\frac{2\cdot 1,4}{0,4}\cdot\frac{8314,32\cdot 2500}{2}\left[1-\left(\frac{1}{300}\right)^{\frac{0,4}{1,4}}\right]}$$

$$= \underline{\underline{7647,5\ m/s}}$$

* pressure in nozzle exit

$$\dot m = \frac{p_c \cdot A_t}{c^*} \qquad \frac{p_e}{p_c} = \frac{1}{300} \Leftrightarrow p_e = \frac{10^6}{300} = \underline{\underline{3333\,Pa}}$$

* pressure thrust:

$$F_p = (p_e - \underbrace{\cancel{p_a}}_{=0})\, A_e = 3333\,\frac{N}{m^2} \cdot \frac{\pi}{4}(0{,}3)^2\,m^2 \cdot \cancel{\frac{2}{1{,}92\,kg/s}}$$

$$= \underline{\underline{235{,}6\,N}}$$

* effective specific impulse:

$$I_{sp} = \frac{F}{\dot m \cdot g_0} = \frac{\dot m \cdot v_e + (p_e - p_a)\,A_e}{\dot m \cdot g_0} = \frac{1{,}92 \cdot 7647{,}5 + 23}{1{,}92 \cdot 9{,}80665}$$

$$= \underline{\underline{792{,}3\,s}}$$

$\Rightarrow$ required specific impulse is not met!!!

6.4.3 Electro Thermal Rocket

geg: c^*, p_c, expansion ratio, A_t, D_t, F

gevr: a) P_{total}

$$P_t = \dot{m}\, c_p \cdot \Delta T = \cancel{\frac{p_c A_t}{c^*}} = \frac{F}{W} \cdot c_p \cdot \Delta T$$

? kg/kmol ≅ g/kmol

$$= \frac{1}{2950} \cdot \frac{33}{11} \cdot \boxed{10^3} \cdot 1200 = \underline{\underline{1220{,}3\ W}}$$

b) $$v_e = \sqrt{\frac{2\gamma}{\gamma-1}\,\frac{R_A\, T_c}{M}\left[1-\left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

figuur $\Rightarrow \frac{p_e}{p_c} = \frac{1}{2400}$

$$= \sqrt{\frac{2\cdot 1{,}3}{1{,}3-1}\,\frac{8314\cdot 1500}{11}\left[1-\left(\frac{1}{2400}\right)^{\frac{0{,}3}{1{,}3}}\right]}$$

$$= 2862{,}6\ m/s$$

$$W = \frac{F}{\dot{m}} \quad ; \quad F = \dot{m}\, v_e + (p_e - \overset{\approx 0}{p_a})\, A_e$$

$$= \frac{1}{2950} \cdot 2862{,}6 + \left(\frac{20\cdot 10^5}{2400}\right) \cdot 2{,}7 \cdot 10^{-6}\, m^2 \cdot 100$$

$$= 1{,}195\ N$$

So, $$w = \frac{F}{\dot{m}} = \frac{1{,}2}{\frac{1}{2950}} = 3526{,}35\ m/s > 2950\ m/s$$

!! $\Rightarrow$ MORE than sufficient (1,2 i.p.v 1 Newton)

3526 m/s i.p.v 2950 m/s

c) Required power will be less, because when Hydrazin decompose, energy is released

Q. 4.4 Nuclear-Thermal Rocket Motor

geg: Fvac, w, mass, η, T

a) Jet Power:

$$P_j = \frac{1}{2} \dot{m} w^2 = \frac{1}{2} F w = 0{,}5 \cdot 35 \cdot 10^3 \cdot 9000 = \underline{\underline{157{,}5\,MW}}$$

b) input power:

$$P_{in} = \frac{P_j}{\eta} = \frac{157{,}5}{0{,}8} = \underline{196{,}9\,MW}$$

c) specific power:

$$P_{sp} = \frac{P_{in}}{m_{sys}} = 0{,}098 \frac{MW}{kg} = 98{,}4\ kW/kg$$

d) Nozzle area expansion ratio:

$$V_e = W = 9000\ m/s$$

$$9000 = \boxed{V_e} = \sqrt{\frac{2 \cdot 1{,}4}{1{,}4-1} \, \frac{8314 \cdot 3000}{2} \left(1 - \left(\frac{p_e}{p_c}\right)^{\frac{1{,}4-1}{1{,}4}}\right)}$$

$$9000 = \sqrt{87297000 \left(1 - \left(\frac{p_e}{p_c}\right)^{\frac{0{,}4}{1{,}4}}\right)}$$

$$\Leftrightarrow \frac{(9000)^2}{87297000} = -1 + \left(\frac{p_e}{p_c}\right)^{\frac{0{,}4}{1{,}4}}$$

$$\left(1 - \frac{9000^2}{87297000}\right)^{\frac{1{,}4}{0{,}4}} = \frac{p_e}{p_c} = 0{,}0001 = 1{,}0 \cdot 10^{-4}$$

$\nearrow$ aflezen ≈ 140 $\boxed{?}$

6.4.5 Electro-Static Thruster:

geg: Xenon → $F = 25\,mN = 25\cdot10^{-3}\,N$
$w = 32000\,m/s$
$\eta = 0{,}8$
η propulsion website

a) mass flow: $\dot{m}_{ion} = \frac{F}{W} = \frac{25\cdot10^{-3}}{32000\,m/s} = 7{,}8\cdot10^{-7}\,kg/s$

b) total mass flow: $\dot{m}_t = \frac{7{,}8\cdot10^{-7}\,kg/s}{0{,}8} = 9{,}76\cdot10^{-7}\,kg/s$

c) Jet Power: $P_j = \frac{1}{2}\dot{m}_{ion}w^2 = \frac{1}{2}\,\cancel{9{,}76\cdot10^{-7}}\cdot(32000)^2$

$= \cancel{500\,W} = 400\,W$

d) η_{thrust} ⟶ syllabus ($\simeq 50\,\%$)

e) $P_i = \frac{400\,W}{0{,}5} = 800\,W$

f) $w = \sqrt{\frac{2q\Delta V}{m_q}}$ met $m_q = \frac{M}{N_A} = \frac{131{,}3\cdot10^{-3}}{6\cdot10^{23}} = 2{,}19\cdot10^{-25}\,kg$

→ $q = e = 1{,}6\cdot10^{-19}$ Coulomb

$w = \cancel{\sqrt{\;}} \Leftrightarrow \Delta V = \frac{w^2\cdot m_q}{2q} = \frac{32000^2\cdot2{,}19\cdot10^{-25}}{2\cdot1{,}6\cdot10^{-19}}$

$= \underline{\underline{7008\,\text{Volt}}}$

8) $I_B = \overset{\dot{m}_{ion}}{\eta_m}\,\frac{\dot{m}}{M}\cdot N_A\cdot q = \frac{7{,}8\cdot10^{-7}}{131{,}3\cdot10^{-3}}\cdot6\cdot10^{23}\cdot1{,}6\cdot10^{-19} = \underline{\underline{0{,}57A}}$

6.5 System Sizing and Dimensioning

6.5.1 Introductory Questions

→ zie antwoorden Gilles

6.5.2 Propulsion System Selection

→ { zie antwoorden Gilles
{ dennis, larry

6.5.3 Liquid Propulsion System Sizing

geg: $F_{vac} = 1125\,kN$, $t_b = 590\,s$, $I_{sp,vac} = 430\,s$
~~[illegible]~~
mixture ratio = 5,1   mass engine = 1475 kg
length = 3 m, exit diameter 1,76 m

opl ① propellant mass (including margin)

$$I_{sp} = \frac{w}{g_0} \Rightarrow w = I_{sp} \cdot g_0 = 430 \cdot 9{,}81 = 4218{,}3\,m/s$$

$$\dot m = \frac{F}{w} = \frac{1125 \cdot 10^3\,N}{4218{,}3\,m/s} = 266{,}69\ [kg/s]$$

$$\Rightarrow m_{tot} = \dot m \cdot \Delta t = 266{,}7\,\frac{kg}{s}\, 590\,s = \underline{157350\,kg}$$

+3% margin = 162070,6 kg

$$162071\,kg = x + y = 5{,}1y + y = (5{,}1+1)y$$

$\Leftrightarrow$ { $y = 26569\,kg$ hydrogen?
$\Leftrightarrow$ { $x = 135502\,kg$ oxigen?   zie pg 21 gilles

6.5.4 Liquid Rocket Engine Characteristics

$F_{vac} = 5\,MN$ LOX & kerosene

$\Rightarrow$ web pages $\Rightarrow$ dry mass

RD 170 = 7,91 MN vacuum thrust ; m = 9750 kg
RD 180 = 4,152 MN " " ; m = 5393 kg

Dus: $\frac{m}{F} \approx 1270$

$\Rightarrow m_{5MN} = 5 \cdot 1270 \approx \underline{\underline{6350\ kg}}$

6.5.5 Solid Rocket Sizing

geg: launch mass, to ~~[illegible]~~ GTO, ΔV, a_{max}
I_{sp} ; ρ_{prop}

opl: a) Propellant Mass:

$$\Delta V = w \ln \frac{M_0}{M_e}$$

? $M_0 = M_e \cdot e^{\frac{\Delta V}{w}}$; met $w = I_{sp} \cdot g_0$

$$\Rightarrow M_e = \frac{6000\ kg}{e^{\frac{1890}{300 \cdot 9,81}}} = 3221,8\ kg$$

$$\Rightarrow M_p = M_0 - M_e = \underline{\underline{2778\ kg}}$$

* idem + sliver mass

A2 p107 } For solids: sliver fraction, λ_s, defined as ratio of propellant mass remaining behind to initial propellant mass. range is 0,05 - 0,1 (5-10%)

selecting a sliverpercentage of 8%

$M_p = 2778 \cdot 1{,}08 = 3000$ kg

* Dry motor mass (loaded mass of motor - propellant mass)

assume $\alpha = [0{,}05 - \overset{?}{\boxed{0{,}12}}]$, selecting $\alpha = 0{,}1$

pg 100 A2

$$M_{dry} = \frac{1}{1-0{,}1} \cdot 3000 = \underline{\underline{3333 \text{ kg}}}$$

$$\Rightarrow \underline{M_{engine}} = M_{dry} - M_{propellant} = 3333 - 3000 = \underline{\underline{333 \text{ kg}}}$$

* Propellant Volume V_p:

$$V_p = \frac{m_p}{\rho_p} = \frac{3000 \text{ kg}}{1600 \text{ kg/m}^3} = \underline{\underline{1{,}875 \text{ m}^3}}$$

* Motor Volume, V_M:

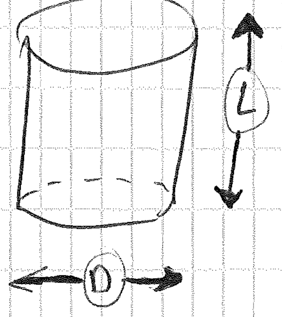
p 106 A2

selecting a conservative estimate of 0,85 (shell volume ratio)

$$\Rightarrow \text{motor } \frac{1}{0{,}85} \text{ greater} \Rightarrow \frac{1{,}875}{0{,}85} = \underline{\underline{2{,}21 \text{ m}^3}}$$

* motor dimensions:

assume: cylindrical motor envelope with an $\frac{L}{D}$ of 1,4 comparable to that of other kick motors.



$$\frac{L}{D} = 1,4 \Rightarrow D = \frac{L}{1,4}$$

$$V = \frac{\pi}{4} D^2 \cdot L = \frac{\pi}{4}\left(\frac{L}{1,4}\right)^2 \cdot L = 2,21 \, m^3$$

$$\Leftrightarrow \frac{\pi}{4 \cdot 1,96} L^3 = 2,21 \, m^3 \Leftrightarrow L = \sqrt[3]{\frac{2,21 \cdot 4 \cdot 1,96}{\pi}}$$

$$= \underline{\underline{1,77 \, m}}$$

$$\Leftrightarrow D = \frac{1,77 \, m}{1,4} = \underline{\underline{1,26 \, m}}$$

solutions check!

* motor (max) thrust & burn (thrust) time:

$$F = (M_0 - M_p) \cdot 3 \cdot 9,81 = (6000 - 2778) \cdot 3 \cdot 9,81 = \boxed{\underline{\underline{94,8}}} \text{ kN}$$

bs $M_p \cdot 3 \cdot 9,81 = 81,7$ kN

$$F = \dot{m} \, w \Rightarrow m = \frac{F}{w} = \frac{94,8 \cdot 10^3}{300 \cdot 9,81} = 32,2 \, [kg/s]$$

$$\Delta t = \frac{2778}{32,2} = \underline{\underline{86,3 \, s}}$$

constant acc $\Rightarrow$ burntime = shorter!

* mass of motor in case the wall is made from steel with a tensile ultimate strength of <u>860 MPa</u> and a density of 7860 kg/m³

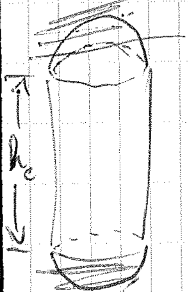
blz 152 ? where to find 43-71 bar range

$\sigma = \frac{P \cdot D}{2t} \cdot j$, assume $P = 55 \text{ bar}$, $j = 2$

$\Rightarrow t = \frac{P \cdot D}{2\sigma} \cdot j = \frac{P \cdot D}{\sigma} = \frac{55 \cdot 10^5 \text{ Pa} \; 1,28 \text{ m}}{860 \cdot 10^6 \text{ Pa}} = \underline{8,05 \text{ mm}}$

$\text{Pa} = \frac{N}{m^2}$

- $A_{surface} = \pi D h_c + \overset{2 \cdot \pi r^2}{2 \cdot \frac{\pi}{4}\left(\frac{D}{\cancel{2}}\right)^2} = \pi D h_c + \pi D^2 \frac{\cancel{2}}{4}$



~~= 13,736 m²~~ ~~A 14,78~~

$\boxed{= 9,5 \text{ m}^2}$

$\Rightarrow V_{engine} = 9,5 \text{ m}^2 \cdot 8,05 \cdot 10^{-3} \text{ m} = 0,0765 \text{ m}^3$

$\Rightarrow mass = 7860 \frac{kg}{m^3} \cdot V_{engine} = \underline{60,1 \text{ kg}}$

- * <u>Cost</u> = 0,0171 \$ / Ns total impulse

p 166 A2

$I = F \cdot \Delta t = 84,4 \cdot 10^3 \text{ N} \cdot 100 \text{ s} = \underline{8,44 \text{ MN}}$

p152 A2

Total Cost = <u>161 424 \$</u>

$\boxed{\text{Reliability} = 0,9841}$ ~~0,9776~~ ~~0,9925~~

~~0,9744~~

6.5.6 Hybrid Rocket System Mass & Operation Time

~~geg~~: Mdry, ΔV, Isp, net mass fraction

a) M_p, required:

$$\Delta V = w \ln \frac{M_0}{M_e} \Leftrightarrow M_e e^{\frac{\Delta V}{w}} = M_0$$

$$\Leftrightarrow M_0 = 100\,kg \cdot e^{\frac{325}{300 \cdot 9,81}} = 111,7\,kg$$

$$\Rightarrow M_p = M_0 - M_e = 11,7\,kg$$

b) $K_d = 0,10$; $K_p = 1 - K_d = 1 - 0,10 = 0,9$

$$\frac{K_d}{K_p} = \frac{M_{dry}}{M_p} \Rightarrow M_{dry} = \frac{0,1}{0,9} \cdot 11,7\,kg = \underline{\underline{1,297\,kg}}$$

$$M_{tot} = M_p + M_{dry} = \underline{\underline{12,997\,kg}}$$

c) minimum total operation time: $a_{max} = 0,5\,g_0$

1) cte acc : $\Delta t = \frac{\Delta V}{a} = \frac{325}{\frac{1}{2} 9,81} = \underline{\underline{66,3\,s}}$

2) const force : $F = m_{dry} \cdot a = 100 \cdot \frac{1}{2} g_0 = 490\,N$

hybrid ≈ 3000 m/s $\Rightarrow \dot{m} = \frac{F}{w} = \frac{490}{3000} = 0,1635\,\frac{kg}{s}$

$$\Delta t = \frac{11,7}{0,1635} = \underline{\underline{71,6\,s}}$$

6.5.7 Solar Collector Sizing

geg: $D = 30\,m$, specif mass $0{,}15\ \frac{kg}{m^2}$, efficiency: 80%

a) Total power received by the collector:

$$P_{received} = \frac{\pi}{4} D^2 \cdot S \qquad \text{met } S @ 1AU = 1{,}4\ kW/m^2$$

$$= \frac{\pi}{4} \cdot 30^2 \cdot 1{,}4 = 989{,}6\ kW$$

b) Total power collected:

$$P_{coll.} = 989{,}6 \cdot 0{,}8 = 791{,}7\ kW$$

c) Total collector mass:

$$m_{collector} = V_{collector} \cdot m_{spec} = \frac{\pi}{4}(30)^2 \cdot 0{,}15$$

$$= \underline{\underline{106\ kg}}$$

d) Specific Power collector:

$$P_{spec} = \frac{P_{tot}}{m} = \frac{791{,}7\ kW}{106\ kg} = \underline{\underline{7{,}47\ kW/kg}}$$

6.5.8 Separately Powered Propulsion System

geg: 10 motors, each 1N thrust, $w = 20\,km/s$, $\eta_j = 0{,}8$, $m_{tot} = 9860\,kg$

a) Required input power per motor:

$$P_j = \frac{1}{2} m\, w^2 = \frac{1}{2} F\, w = \frac{1}{2} \cdot 1 \cdot 20000 = \underline{10\ \frac{kW}{motor}}$$

$$P_{in} = \frac{P_j}{\eta_{motor}} = \frac{10\ kW}{0{,}8} = \underline{\underline{12{,}5\ kW}}\ /motor$$

b) Specific power of the system (based on total input power)

$$P_{spec} = \frac{P_{in}}{m_{total}} = \frac{10 \cdot 12{,}5\ kW}{9860\ kg} = 0{,}012677\ \frac{kW}{kg}$$

$$= \underline{\underline{12{,}677}}\ \frac{W}{kg}$$

c) Optimum exhaust velocity, assuming $t_{thrust} = 180\,days$

$$w = \sqrt{\frac{1}{\varepsilon}} = \sqrt{\frac{2\eta \cdot t}{\alpha}} = \sqrt{\frac{2 \cdot 0{,}8 \cdot 180 \cdot 24 \cdot 60 \cdot 60}{0{,}079}}$$

$$\frac{1}{P_{spec}} = 0{,}079$$

$$= 17{,}76\ \frac{km}{s}$$

d) Optimum required input power; F = cte:

$$P_j = \frac{1}{2} \cdot 10 \cdot 17{,}76 \cdot 10^3 = 88{,}8\ kW$$

$$P_{in} = \frac{P_j}{\eta} = 111\ kW$$

6.5.9 Electric System Sizing

geg: $M_{dry} = 5000\,kg$ $\frac{F}{weight} = 2 \cdot 10^{-4}$

LEO → GEO in 30 days $\Delta V = 5{,}7\,km/s$

a) optimum exhaust velocity

$$w = \sqrt{\frac{1}{\varepsilon}} = \sqrt{\frac{2 \cdot \eta \cdot t}{\alpha}}$$

$$m = 20\,kg/kW + 30\,\%$$
$$= 0{,}02\,kg/W + 30\,\% = \alpha = 0{,}026\,\frac{kg}{W}, \quad \eta = 1$$

$$\Rightarrow w = \sqrt{\frac{2 \cdot 1 \cdot 30 \cdot 24 \cdot 60 \cdot 60}{0{,}026}} = \underline{\underline{14{,}12\,km/s}}$$

b) Required Propellant mass:

$$\Delta V = w \ln\left(\frac{M_0}{M_e}\right) \Leftrightarrow M_0 = M_e \cdot e^{\left(\frac{\Delta V}{w}\right)}$$

$$\Leftrightarrow M_0 = 5000 \cdot e^{\frac{5700}{14120}} = 7486{,}6\,kg$$

$$M_{p,req} = M_0 - M_e = 2486{,}6\,kg$$

$$\dot{m} = \frac{m}{\Delta t} = \frac{2486{,}6}{30 \cdot 24 \cdot 60^2} = 0{,}959 \left[\frac{g}{s}\right]$$

$$F_{thrust} = \dot{m}\,[kg] \cdot w = \underline{\underline{10{,}8\,N}}$$

$$\text{thrust eff} = 0{,}8 \Rightarrow w = \underline{14{,}12\,km/s \cdot 0{,}8} = 11{,}296\,km/s$$

* OVT mass @ mission start:

$$P_j = \frac{1}{2}\dot{m}w^2 = \frac{1}{2}Fw = \frac{1}{2}\boxed{\cdot 10,8} \cdot 11286 = \underline{\underline{60998,4}}$$

$$\underline{\underline{\approx 61\ kW}}$$

assume: Thrust eff = 50% ⇒ $P_{in} = \underline{\underline{121,996\ kW}}$

122 × 20 = 2440 kg or 48,8% of the dry mas

* mass of the power plant:

$\underline{121,996\ kW} \times 20\ kg/kW = \underline{\underline{2440\ kg}}$

6.6 Alternative Propulsion Systems

6.6.1 Solar Flux

$$\mathcal{J} = \frac{P}{4\pi d^2} \quad ; \quad P = 3,856 \cdot 10^{26}\ W$$

SSE

$$\Rightarrow S_{Earth} = \frac{3,856 \cdot 10^{26}}{4 \cdot \pi \cdot (1,496 \cdot 10^{11})^2} = 1371\ \frac{W}{m^2}$$

$$S_{Mercury} = 1371\ \frac{W}{m^2} \cdot \frac{1}{(0,3871)^2} = 9149,9\ \frac{W}{m^2}$$

$$S_{Mars} = 1371\ \frac{W}{m^2} \cdot \frac{1}{(1,5237)^2} = \overset{OK}{\cancel{590,6}}\ \frac{W}{m^2}$$

$$S_{Jupiter} = 1371\ \frac{W}{m^2} \cdot \frac{1}{(\underset{5,2028}{\cancel{17,9}})^2} = \overset{50,65}{\cancel{4,28}}\ \frac{W}{m^2}$$

$$S_{Pluto} = 1371\ \frac{W}{m^2} \cdot \frac{1}{(39,5294)^2} = 0,88\ \frac{W}{m^2}$$

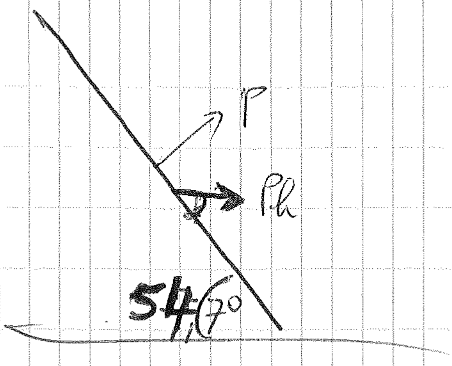
6.6.2 Solar Sailing : Sail Size and Mass

A2
p120

$m = 533$ kg (excl sail)
$a = 0,3\ mm/s^2$
ΔV km/s
$\Rightarrow A_{acc}$

opl : reflection 85% assumed (p 120)
absorptie : 1 − 0,85 = 15%
opaque ⇒ $\tau = 0$
assume : constant solar flux = 1371 $\frac{W}{m^2}$

??



$p = p_r + p_a + p_i = \frac{S}{c} \cdot \left(2 - \frac{1}{3}\varepsilon\right)$ assume $\varepsilon = 0{,}1$

$= \frac{1371}{300 \cdot 10^6}\left(2 - \frac{1}{3} \cdot 0{,}1\right) = 9\,\mu N/m^2$

$\Rightarrow P_h = \frac{p}{\tan 54{,}7} = 6{,}36\,\mu N/m^2$

$+ m_1 \omega^2 r_1$

~~b) $F_{tension} = m_2 (\mu/r_2)^2 \quad m_2 \omega^2 r_2 = -m_1 (\mu/r_1)^2$~~

~~$m = 20 \times 4{,}9 =$~~

$m = 10\,g/m^2$, $m_{str} = m_{sail}$

$F = m \cdot a$, with $a = 0{,}3\,mm/s^2$

$6{,}36 \cdot 10^{-6} \cdot A_{sail} = \left\{533 + (0{,}01 \cdot A_{sail} \cdot 2)\right\} \cdot 0{,}3 \cdot 10^{-3}$

$Ph \cdot A = m \cdot a$

$\Longleftrightarrow A_{sail} = 444166\,m^2$

$\Longleftrightarrow m_{sail} = 0{,}01 \cdot A_{sail} = \underline{\underline{4441{,}66\ kg}}$

$\rightarrow \Delta V = 15000\,m/s$

$\Delta t = \frac{\Delta V}{a} = \frac{15000}{0{,}3 \cdot 10^{-3}} = 5 \cdot 10^7\,s = \underline{\underline{578{,}7\ dagen}}$

6.6.3 Drag Force by ED Tether:

↗

6.6.4 Space Shuttle ED Tether:

* maximum electrical power produced in orbit

$P = V \times I \qquad I = \frac{V}{R}$

$R = R' \cdot \frac{L}{A} \qquad R' = 20 \cdot 10^{-9}$

$L = 20000$

$A = \frac{\pi}{4} \left(2{,}5 \cdot 10^{-3}\right)^2$

$V = L \cdot v_0 \cdot \frac{B_E R_E}{r^3} \cos \lambda$

$r = 6378{,}14 + 410 = 6788{,}14 \text{ km}$ { c.g. half of tether

$V_{orbit} = 7669$ (SMAD achteraan)

$$V = 20000 \cdot 7669 \cdot \frac{31 \cdot 10^{-6} (6378{,}14)^3}{(6788{,}14)^3} = \underline{\underline{3944{,}2 \text{ V}}}$$

$$R = 20 \cdot 10^{-9} \cdot \frac{20000}{\frac{\pi}{4}\left(2{,}5 \cdot 10^{-3}\right)^2} = 81{,}49$$

$$\Rightarrow P = \frac{V^2}{R} = \frac{(3944)^2}{81{,}49} = 190{,}9 \text{ [kW]}$$

b) $F_{tension} = m_2 \left(\frac{\mu}{r_2}\right)^2 - m_2 \omega^2 r_2 = - m_1 \left(\frac{\mu}{r_1}\right)^2 + m_1 \omega^2 r_1$

$m = 20 \times 4{,}9 = 98\,kg$; $\mu = 398600 \,(km^3/s^2)$

$r = 6788{,}14\,km$

$\omega = 3{,}889\,deg/min \overset{\times \frac{2\pi}{360 \cdot 60}}{=} 1{,}13 \cdot 10^{-3}\,rad/s$

$F_{tension} = \ldots\ldots = \underline{\underline{0{,}2\,N}}$

7. Systems Engineering

7.1

What is the importance of SE?

* SE is an iterative process, wherein all involved disciplines, both technical and non-technical, work together to realize the "best" design.

* Hamann: "a structured & explicit process approach to designing a system."

Important, why?

samenwerken zodat je niet teveel moet veranderen a/h einde ⇒ dit is kostelijk

7.2 Basic Engineering steps

- Define problem/objectives to be reached
- Establish requirements (needs) / requirements generation
- set up options
- evaluate (analyse) design options

(develop specifications
(implementation)

7.3

① bad, not quantifyable
② bad, " "
③ bad, not measurable, not clear!
④ good, clear requirement
⑤ bad! launchvehicle sd.
⑥ bad, not quantifyable
⑦ good
⑧ good

7.4

concept 1, 3 en 5 : zie grenzen!

7.5

communications all over the world internet

- ~~software engineer~~

Telecommunications

- telecommunications payloads
- s/c bus
- launch
- operations

B p57

- SC
- orbit & constellation
- ground segment incl. data distr., ttr., arch.
- project support
- manufacturing ... MAIT
- ~~assembly~~
- Logistics
- product assurance

Hoofdstuk 8: Mission Concept Exploration

8.1

pg 34

space mission segments + functions

Mission segment	Function	Definition
Subject	observe "it"	interaction with payload
Launch segment	transportation	
orbit & constellation	access & coverage	
space segm payload	transfer data	
space segm. bus	service & support	
communications architecture	provide telemetry between space & gr.	
ground segment	on-ground monitoring	
mission operations	human staffing	

8.2

space based navigation mission

⇒ low cost, reliable | position determination
velocity
direction of travel

in addition: how to go / time of arrival

typical information ~~[illegible]~~

SMAD p 15

* Functional requirements:
- current position
- travel speed
- direction of travel
- current time
- way to go
- time of arrival

specialty

* Operational requirements:
- availability
- user equipment needed

* contraints:
- ~~availability~~
- reliability
- cost of service

8.3 GPS/NAVSTAR

Transit/NOVA

Main Performance
- lifetime 10 years
- mass: 2040 kg
- cost 30 M$ piece

operational
accuracy 15m - 100m

?

SMAD 504 505

8.4 Mission Concept

observation mission
⇒ disaster areas (monitor)
support workers (info)

① subject: disaster area
② payload: remote sensing equipment for
③ launch system: affected by mass, size, orbit height
④ mission lifetime

8.5 Iridium System Trades

list — Trades made — main criteria used

* 14 verschillende

pg B.294

* Final design solution following from each of the above trades

⑧ Mission concept ⒷⒷ

→ how to satisfy end user's needs

Requirements : pg 16

bandwidth / data rate pg 21
coverage

availability : pg 24

RAMS = Reliability - Availability - Maintainability - Safety

$$\frac{\text{distance}}{\text{speed of light}} = \text{travel time (signal)}$$

Excercices ⇒ web pages

⑦ Systems Engineering

⑨ Remote Sensing

bands pg 72

Radiation: Planck / Spectral radiance 78-79
Spectral signature
selecting wave bands : VIS Radar
IR
Microwave

passive & active instruments pg 86

spatial/angular resolution $= 2\theta_r h$

ground resolution

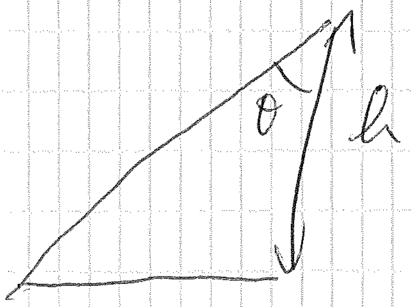
instrument requirements pg 89 checklist.

instruments

optics design

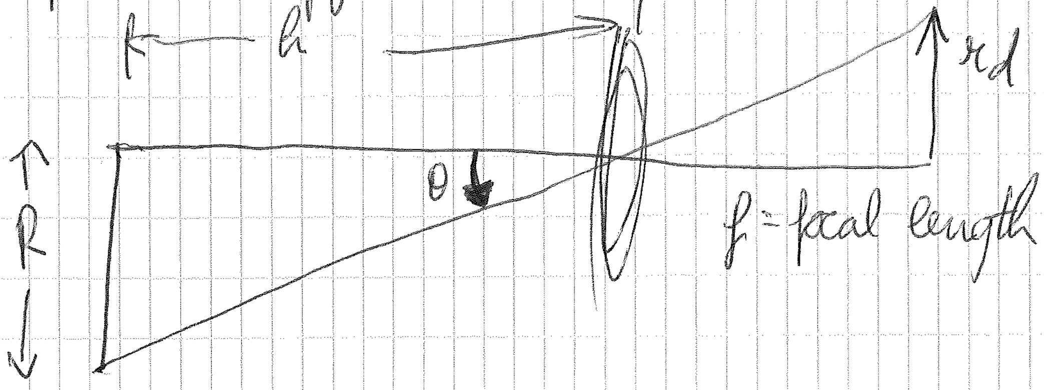
$$X = \frac{2{,}44 \cdot \lambda}{D} \cdot h / \cos\theta \cdot q$$

X = nadir ground resolution
D = aperture size
h = height
q = quality



Optics design

formules pg 100 - 101



$$FOV = 2\theta \quad \wedge \quad \theta = \arctan \frac{R}{h} = \arctan \frac{rd}{f}$$

$$t_{sc} = t_d = \frac{X}{V_N}$$

scanning

Data Rate

pg 112

Instrument sizing

pg 114

Hoofdstuk 9: Instrumentation

9.1 Requirements

B pg 89, (SMAD p 250)

9.2

a) visible light	+	−	−	B, pg 84
b) radar	+	−	≥	

9.3

dry soil, wet soil, vegetation or water

option 1: select one waveband

⇒ 0,4 - 0,8 μm to detect all four.
best option @ 0,6 μm

option 2: select two wavebands

1) 0,4 - 0,8 μm ; best 0,5-0,6 where water has its optimum
2) 2,2 μm : good reflectance. good discriminating power

6.
in case of water: no reflectance → detect if the signal of the lower wavelength is about water.

option 3: adding another wavelength
between wet soil & vegetation ⇒ 0,8 μm

9.4

Parameters diffraction limit

D (camera) , with ground resolution 0,5 m (nadir)
orbit 1000 km

$$\theta_r = \frac{1{,}22 \cdot \lambda}{D} \quad \begin{matrix} \text{— wavelength} \\ \text{— lense diameter} \end{matrix}$$

$$X = \frac{2{,}44 \cdot \lambda}{D} \cdot h \;/\; \cos\theta^{s} \cdot \boxed{\eta} \rightarrow 0{,}5 < \eta < 2$$

$\Rightarrow \eta = 1{,}1$ is good

$$\Rightarrow 0{,}5 \cancel{m} = 2{,}44 \cdot \frac{1000 \cdot 10^3 \cdot \lambda}{D}$$

$$\Rightarrow D = \frac{2{,}44}{0{,}5} \cdot 1000 \cdot 10^3 \,\lambda = \underline{\underline{4{,}88 \cdot \cancel{1000}\, 10^6 \,\lambda}}$$

bij $\lambda = 0{,}5 \mu m$ (visible light) $\Rightarrow D = 2{,}44$ **m**

9.5

panchromatic
1:25000 → 1m x 1m grootte
ground resolution **5m**

? min. amount of data needed for single map in 8 grey scales

1cm op map = 250m
⇒ covers 25000m x 25000m = 25 km x 25 km
for ground resolution of 5m = 5000 x 5000 resol. elements

8 grey scales ⇒ 3 bits digital format

$\Rightarrow 3 \times 5000 \times 5000 = 75$ Mbits $= 9375000$ bytes $\overset{:1024}{=}$ 9 155,3 KB

$= 8{,}94$ MByte

9.6

SMAD pg 269 - 270

9.7

panchromatic
circular orbit @ 800 km
6000 res. elem. (across track dir)
ground res. 15 m (nadir)
10 bit dynamic range

⇒ gevr: ....
opl: a) angular resolution

??? $\left(\theta_r = 1,22 \frac{\lambda}{D}\right)$ ~~$\theta_r = \arctan \frac{R}{h} = \text{arctg}$~~

B, pg 87 $\Rightarrow X = 2\theta_r \cdot h$

$\Rightarrow \theta_r = \arctan\left(\frac{X}{2 \cdot h}\right) = \arctan\left(\frac{15}{2 \cdot 800 \cdot 10^3}\right)$

$= 5,36 \cdot 10^{-4}$

b) field of view

$FOV = 2\theta_r = 0,00107° \text{ deg}$

c) Max ground resolution cross track

$Z_c = \frac{\theta_x}{IFOV} \Rightarrow 6000 = \frac{\theta_x}{1,074 \cdot 10^{-3}} \Leftrightarrow \theta_x = 6,446°$

d) Data Rate /s

10 bits/pixel

$DR = Z \cdot B = Z_a \cdot Z_c \cdot B$

$= \frac{V_n}{y} \cdot 6000 \cdot 10 = 441{,}44 \cdot 6000 \cdot 10$

$= 26{,}5 \frac{\text{Mbit}}{s} = 26486629{,}97 \frac{\text{bits}}{s}$ (~~= 3,15~~ MByte)

$\frac{V_n}{y} = \frac{3{,}569 \text{ deg}/\text{min} \cdot 6378{,}14 \text{ km}}{15} =$

$= \frac{3{,}568 \times 2\pi \times 6378{,}14 \cdot 10^3}{60 \times 360 \times 15} = 441{,}44 \text{ m/s}$

e) pixel dwell time

1) pushbroom scanning

$t_d = \frac{1}{Z_a} = \frac{1}{442} = 2{,}26 \cdot 10^3$ s/line

2) whiskbroom

$t_d = \frac{1}{Z_a} \cdot \frac{1}{Z_c} = \frac{1}{442 \cdot 6000} = 3{,}77 \cdot 10^{-7}$ s/res. el.

9.8 idem @ 12 km @ V = 200 m/s

a) $\theta_x \overset{\text{arctg}}{=} \left(\frac{X}{2h}\right) = \text{arctg}\left(\frac{15}{24000}\right) = 0{,}0358$

b) $FOV = 2\theta = 0{,}07$ deg

c) $6000 \cdot 0{,}07 = \theta_x$ $\left(Z_c = \frac{\theta_x}{PFOV} \right.$

d) $DR = Z_a \cdot Z_c \cdot B \cdot N_c = \frac{200}{15} \cdot 6000 \cdot 10 \cdot 1 = 800\,000$ bits/s $= 0{,}8$ Mbit/s

e) 1) $t_d = \frac{1}{Z_a} = \frac{15}{200}$

2) $t_d = \frac{1}{Z_a \cdot Z_c} = \frac{15}{200 \cdot}$

9.9 Multi-colour imager

colours : 3 vis
1 IR

s/c @ 800 km
swath width 185 km
gr. res. in nadir of 15 m @ 1 μm wavelength
$B = 10$ bits

$\rightarrow$ $PFOV = 2\vartheta_r = 2 \, \mathrm{arctg}\left(\frac{7{,}5}{800 \cdot 10^3}\right) = 0{,}00107\,°$

* $X' = 2{,}44 \frac{h\lambda}{D} \Leftrightarrow 15 = \frac{2{,}44 \cdot 800 \cdot 10^3 \cdot 10^{-6}}{D}$

$\Leftrightarrow D = 0{,}13 \text{ m}$

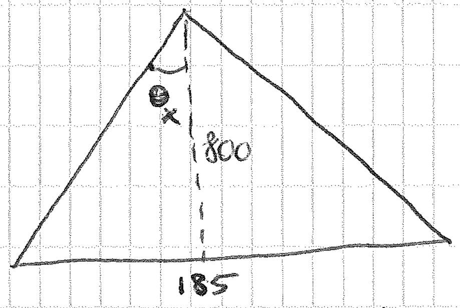
* $d = \frac{2{,}44 \, \lambda \, f}{D} \cdot q$

$15 \cdot 10^{-6} = \frac{2{,}44 \cdot 10^{-6} \cdot f \cdot 1}{0{,}13} \Leftrightarrow f = \underline{\underline{0{,}8 \text{ m}}}$

* $DR = Z_a \cdot Z_c \cdot B \cdot N_c$

$Z_a = \frac{V_n}{y} = 442$

$Z_c = \frac{\theta_x}{\cancel{PFOV}} = \frac{13{,}2}{0{,}00107} = 12\,328$



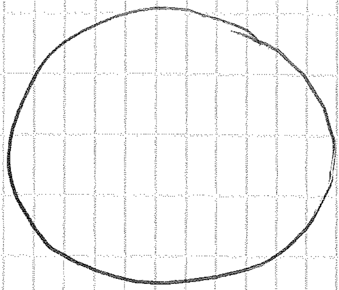
$\theta_x = 2 \arctan\left(\frac{185/2}{800}\right)$

$= 13{,}2$

$\Rightarrow DR = 217$ MBits/s

9.10

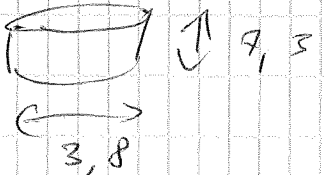
* aperture size 2,5m



$R = A$

SMAD   Pg 275   tab 9.13

Solar Optical telescope



$R = \frac{A_i}{A_0} = \frac{\pi/4\ (2,5)^2}{\pi/4\ (1,5)^2} = 4$

$L_0 = V_0^{1/3} = \left(\frac{\pi}{4}\ 3,8^2 \cdot 7,3\right)^{1/3} = 4,36\ m$

$L_i = R \cdot L_0 = 4 \cdot 4,36\ m = 17,43$

$S = L_i^2 = (17,43)^2 = 303,8\ m^2$

$V = L_i^3 = (17,43)^3 = 5295,3\ m^3$

$K = 1$, because $R > 0,5$

$M = K R^3 \cdot M_0 = 1 \cdot 4^3 \cdot 6600 = 422,4$ tons

$P = K R^3 \cdot P_0 = 1 \cdot 4^3 \cdot 2000 = 128$ (kW)

Hoofdstuk 10 : Bus Design

10.1

Propulsion
TT&C
Guidance & Navigation
Command & Data Handling
Attitude determination & Control
Thermal Control
Electrical Power
Structure & Mechanisms

uit leg zie

AE1-801 : part 1
B, pg 129

10.2

10.3

120 FM channels
3 antennas
1 kg / FM channel
40 kg / antenna

Total vehicle mass: 690 kg
a) $\Delta V = 535$ m/s
$I_{sp} = 295$ s

① vehicle dry mass

$$\Delta V = I_{sp} \cdot g_0 \cdot \ln \Lambda \Rightarrow 535 = 295 \cdot 10 \cdot \ln \Lambda$$

$$\Rightarrow e^{\frac{535}{2950}} = \Lambda = 1{,}1988$$

$$\Lambda = \frac{M_0}{M_e} = \frac{690 \text{ kg}}{M_e} = 1{,}1988$$

$$\Leftrightarrow M_E = \frac{690}{1{,}1988} = 575{,}6 \text{ kg}$$

② Payload mass:

120 kg + 120 kg = 240 kg

③ bus subsystems:

575,6 - 240 = 335,5 kg

"<u>Preliminary</u> <u>Mass</u> <u>Budget</u>" total bus: 69,3%

		omzetten x $\frac{100}{69,3}$		Mass
structures	: 21%	→	30,3%	101,6 kg
Thermal	: 4,2%		6,06%	20,3 kg
Power	: 28,8%		41,56%	139,43 kg
TT&C	: 4,2%		6,06%	20,3 kg
AOCS	: 6,0%		8,66%	29,05 kg
Prop	: 5,1%		7,36%	24,7 kg
				335,4 kg

Mass Bus: ~~575,6 kg~~ 335,5 kg

Reduction of uncertainty:

- limiting the s/c used to develop our mass estimate to those ~~veh~~ vehicles that are clearly comparable to the Iridium s/c.

- increasing the number of s/c involved (of the same size-cathegory)

- develop more precise mass estimation methods.

10.4 small sat. : 50 – 100 kg

4 comparable s/c

⇒ determine average payload-mass to dry ratio and dry mass distr. over the various vehicle subsystems

---

855 Posat 1 : 50 kg : verdeling pg 896
Bremsat : 68 kg : " "
Orbcomm : 47 kg : " "

Alle info van p 896 **SMAD**

Alle info van B, pg 155

10.5 Propellant Mass Estimation and Budgetting

m: 2000 kg – 3000 kg
life: 15 years
launcher Proton M   5500 into space (GTO)

(Apogee kick – NS, EW station keeping, momentum wheel unloading
End of life disposal)

~~gg~~ : W = 2000 m/s station keeping, mom. wheel, en f/life
W = 3000 m/s apogee kick

gevr: ΔV budget, M_p, Proton suitable ?

ΔV budget:

Apogee kick: GTO to GEO : 1,8 km/s
station keeping : 50 - 55 m/s / year = 825 m/s
momentum wheel unloading : 2 - 6 m/s / year = 90 m/s
end of life disposal (assumption: Firesat): 200 m/s

① Dry mass: 3000 kg

monoprop.

$$\Delta V = w \ln\left(\frac{M_0}{M_e}\right) \Leftrightarrow M_0 = M_e \, e^{\left(\frac{\Delta v}{w}\right)}$$
$$= 3000\,\text{kg} \cdot e^{\frac{1115}{2000}}$$
$$= \underline{5238{,}9\,\text{kg}}$$

$\Rightarrow$ hydrazine propellant mass $\cong M_0$ - Dry mass
$\cong 2238{,}9$ kg

② Apogee kick motor

$$M_0 = 5238{,}9\,\text{kg} \cdot e^{\left(\frac{\Delta v}{w}\right)} = 5238{,}9 \cdot e^{\frac{1800}{3000}} = 9545{,}9\,\text{kg}$$

Dry mass: 2000 kg

① $\Delta V = w \ln\left(\frac{M_0}{M_e}\right) \Leftrightarrow M_0 = M_e \, e^{\left(\frac{\Delta v}{w}\right)} = 2000 \cdot e^{\frac{1115}{2000}}$
$= 3492{,}6$ kg

$\Rightarrow$ hydrazine prop mass $\cong M_0 - M_e = 1492{,}6$ kg

② Apogee kick motor: $M_0 = M_e \, e^{\left(\frac{\Delta v}{w}\right)} = 3492{,}6\,\text{kg} \; e^{\frac{1800}{3000}}$
$= 6363{,}9$ kg ▷ 6000 kg 5500 kg

10.6

total input power = 6,0 kW

OPLOSSING GEVR

10.7

idem

11.2 pg 166

dedicated

shared
→ similar orbital req.

piggyback
→ low cost, limited mass, own deployment mechanism

11.3

	Launcher 1	Launcher 2
m = 200 kg	250	300
	M 12 $	M 13 $
2 vehicles in space	R = 0,85	0,94

⇒ ① R = 0,7225 24 M$
② R = 0,8836 26 M $

select ② : reliability & misschien nog piggyback mee laten gaan voor 2M$

11.4 Parameters

zie solutions

Hoofdstuk 12

Risk analysis Process

① Risk identification : define char. of a certain risk
② Risk estimation : quantitative
③ Risk assesment : acceptance levels   acceptability
④ Risk Evaluation : judgements about significance
⑤ Risk mitigation : process of reducing the level of risk

● **12.4**

total budget = 4,2 M$
estimation of cost = 4 M$

SMAD
p 804

TRL 1 => Relative Risk Level : High
=> Standard deviation about MLE >25%

??

cost estimating uncertainty 0,5 M$

● => total uncertainty $= \sqrt{0,25^2 + 0,12^2} = 0,277 = \underline{\underline{27,7\%}}$

12.5 Risk Matrix

Zie pg 226

Hoofdstuk 11 : Launch Vehicle selection

highest availability

	Launcher 1	Launcher 2
nr flight/yr : L	8	20
R	0,96	0,93
surge rate : S	1,5	2
stand down time : Td	8 months	4 months

$$A = 1 - \left[L\,(1-R)\,T_d \;/\; (1 - 1/S) \right]$$

$$A_1 = 1 - \left[8\,(1-0{,}96) \cdot \frac{8}{12} \;/\; (1 - 1/1{,}5) \right]$$

$$= 0{,}36$$

$$A_2 = 1 - \left[20\,(1-0{,}93) \cdot \frac{4}{12} \;/\; \left(1 - \frac{1}{2}\right) \right]$$

$$= 0{,}067$$

$$\underline{A_1 > A_2} \quad \Rightarrow \text{Launcher 1}$$

13. Reliability

$R(t) = 1 - F(t)$

$\frac{dy}{dt} = -\boxed{\lambda}\, y$ → hazard rate

$\ln y = -\lambda t$

$y = e^{-\lambda t} = R(t)$

MTTF (mean time to failure) $= \frac{1}{\lambda}$

$\text{MTBF} = \frac{\Sigma \text{ oper. time betw. failures}}{\text{Total number of failures}}$

ex.

$R = 0{,}999$

op life 1000 hours

$\Rightarrow \lambda = -\ln(0{,}999)/1000 = 1 \cdot 10^{-6}$ failures/hour

$\text{MTTF} = \frac{1}{10^{-6}} = 10^{6}$ hours $=$ 114,3 years

8 760 hours / year →

⇒ 114 years of testing with 1 failure

≅ 114 items testing for 1 year

≅ or 1140 for 37 days

13.1 operational lifetime 1 year
MTTF = 1,5 year

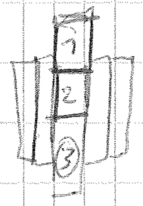
$* \ \lambda = \dfrac{1}{MTTF} = 0,667$

$* \ R = e^{-\lambda t} = e^{-0,667 \cdot 1} = 0,5132 = 51,3\%$

$* \ R = e^{-0,667 \cdot 2} = 0,2634 = 26,3\%$

13.2

soyuz =



4 boosters (parallel)
3 core stages

$R(\text{soyuz}) = 0,968$
$R(1) = 0,998$
$R(2) = 0,998$
$R(3) = R(\text{booster})$

gevr: $R(\text{booster})$

$R(\text{soyuz}) = \left[R(\text{core } 1) \times R(\text{core } 2) \times R(\text{core } 3) \times R(\text{booster } 1) \times \dots \right]$

$\Leftrightarrow R(\text{soyuz}) = 0,996 \ R(\text{unknown})^5$

$\Leftrightarrow 0,968 = 0,996 \ R(\text{unknown})^5$

$\Leftrightarrow \dfrac{0,968}{0,996} = R(\text{unknown})^5$

$\Leftrightarrow 0,972 = R(\text{unknown})^5 \qquad \Leftrightarrow R(\text{unknown}) = 0,9943$

13.3

latching valves in serie 0,99
thrusters 0,98

?
?
?

$$\left.\begin{aligned} R_1 &= (0{,}98)^4 \cdot (0{,}99)^2 = 0{,}904 \\ R_2 &= (0{,}98)^2 \times (0{,}99)^2 = 0{,}941 \end{aligned}\right\} \Rightarrow R = R_1 \cdot R_2 = \underline{\underline{0{,}85}}$$

13.4

?

16 active transponders
4 backup "

mission duration: 5 years
MTTF = 100 000 hours $\Longrightarrow$ $\lambda = \frac{1}{100\,000}$

$$R = e^{-\lambda t} = e^{(-1/100000 \times 5\,\text{year} \times 360\,\text{d.} \times 24\,\text{h})} = \underline{\underline{0{,}6492}}$$

overall payload reliability

$$R = \binom{20}{16}(0{,}649)^{16}(0{,}351)^{20-16} + \binom{20}{17}(0{,}649)^{17}(0{,}351)^{3}$$

$$+ \binom{20}{18}(0{,}649)^{18}(0{,}351)^{2} + \binom{20}{19} 0{,}645^{19} \cdot 0{,}351^{20-19}$$

$$+ \binom{20}{20} 0{,}645^{20} \cdot 1 =$$

13.5

R[fuel cell type] = 99,83%   for 2 day mission

for Power → at least 3 cells are needed.

⇒ 1 additional cell per 3 cells

a) $R = e^{-\lambda t}$

stil R = 99,83

$\Rightarrow 0,9983 = e^{-\lambda 2}$

$\Leftrightarrow \ln(0,9983) = -\lambda \cdot 2$

$\Leftrightarrow \lambda = -\frac{\ln(0,9983)}{2} = +0,000850723$

$R_{18\,days} = e^{-\lambda \cdot 18} = e^{[(-0,000850723)\cdot 18]} = \underline{\underline{0,9848}}$ of $\underline{\underline{98,48\%}}$

b) Reliability of group of 4 cells

$\left(\frac{20!}{16!} = \frac{20 \times 19 \times 18 \times 17 \times \cancel{16!}}{\cancel{16!}}\right)$

3 out of 4 reliability: $R = 0,9848^4 + \binom{4}{3} \cdot 0,9848^3 (1-0,9848)$

$= 94,06\% + 5,8\% = 99,87\%$

c) $R = 1 - (1-0,9987)^N$ with $R \geqslant 0,99999$

⇒ ~~0,99999~~ N = 2 ⇒ $R = 0,9999831 \geqslant 0,99999$

$\overset{\rightarrow \text{maintanance}}{}$

d) MTBM

$\lambda = 0,000850723$

$$MTBF = \frac{1}{\lambda} = 1175 \text{ daeys}$$

$\Rightarrow$ MTBM < MTBF , but not to small, otherwise maintenance costs will be too high.

● **B.6**

			R
bus with :	communications	33,6%	92,77%
	guidance & nav.	18,6%	95,9%
	el. power	18%	96,06%
	C&DH	12,4 %	97,27%
	Thermal	7,6%	98,3%
	propulsion	5,0%	98,89%
	structure	4,8%	98,93%

● $\Rightarrow$ reliability budget so that $R[\text{bus}] = 0,80$

a) all systems equally reliable

b) failure data zie

a) in case of (a) $\Rightarrow$ $R[\text{all systems apart}] = 0,8^{(1/7)} = 0,9686$

b) lifetime 1 jaar $\Rightarrow$ overall failure rate

$$\cancel{R(t) = 1 - F(t)}$$

$$\cancel{e^{-0,000850723} = 1 - F(t) \Leftrightarrow F(t) = -(e^{-0,000850723} - 1)}$$

$$0,8 = e^{-\lambda} \Rightarrow \lambda = -\ln 0,8 = 0,223 \text{ failures/year}$$

33,6 % is attributed to comm

$\Rightarrow$ failure rate $= 0{,}336 \cdot 0{,}223 = \underline{0{,}075}$ failures / year

$\rightarrow R = e^{-0{,}075} = 92{,}77\%$

13.7

operational life = 100 000 hours
R(component) = **0,999**
confidence level $\underline{95\%}$ $\Rightarrow$
overall test duration is not longer than a half year
no failures during test

opl: $R = e^{-\lambda t} \Leftrightarrow 0{,}999 = e^{-\lambda(100000\ \text{hr})}$

$$\Leftrightarrow -\frac{\ln 0{,}999}{100000\ \text{h}} = \lambda = 0{,}00000001$$

$\Rightarrow \text{MTTF} = \frac{1}{\lambda} = 100$ milj. hours

@ 95% confidence, 0 failures allowed

$\Rightarrow 3 \cdot 100$ milj hours $= 300$ milj hours $= \frac{300 \cdot 10^6}{8760}$ ~~dagen~~

= ~~11423 dagen~~ ~~jaar~~ ~~≤ 34 jaar~~ = 34247 jaar

1 item testen voor 34247 jaar

of 34247 items voor 1 jaar of $34247 \cdot 2$ items voor $\frac{1}{2}$ jaar

<u>68493</u> items voor half jaar

14. Costing

SMAD : CH 20

14.1

14.2

5 identical communications sat.

mass payload 360kg → 335 kg elektronics
↳ 25 kg antennas

dry mass bus (excl. payl.) = 1228 kg
↳ incl. 85 kg AKM

learning curve 0,95

? **total space segment cost**

opl :

RDT & E

SMAD 795 1. Payload

1.1 0

1.2 0

1.3 $353,3 \cdot \underline{360} = 127188$

2. S/C $101 \cdot \underline{1228} = 124028$

2.1 $17,8 \; \underline{85}^{0,75} \; (= 498,29)$

3. IA&T $989 + 0,215 \cdot (127188 + 124028) = 55000,44$

4. RL $1,963 \; (127188 + 124028)^{0,841} = 68290,47$

5 GrE $9,262 \; (\;"\;)^{0,642} = 27135,33$

Total = 237672,24 ④

Total,

TFU Cost

1.3 Comm. $140 \cdot 360 = \underline{50400}$ (1)

2. S/C $43 \cdot 1228 = \underline{52804}$ (2)

2.0 $4{,}97 \cdot (85)^{0{,}823} = 140{,}49$

3. IA&T $10{,}4 \cdot (1228 + 360) =$ [illegible] $16515{,}2$

4. Pr. L $0{,}341 \cdot (\underset{(1)+(2)}{[illegible]}) =$ [illegible] $135192{,}6$

5. M

6. LOOS $4{,}9\ (1228 + 360) = 7781{,}2$

TOTAL = 162 693

Production cost = TFU × L

$$B = 1 - \frac{\ln\left(\left(\overset{95\%}{100\%}\right) / 0{,}95\right)}{\ln 2} = 0{,}925999$$

$L = 5^B = 4{,}4386$ [illegible]

Production cost for 5 sat. = TFU × L ≈ ~~162693 × 4,4386~~

1st unit = payload + S/C + IAT = 50400 + 52804 + 16515

= 119719

2nd unit = (unit cost) × 1st unit = 107747,1

$\overset{0{,}90}{}$

3th unit = 0,87 × 119719 = 104155,5

4th = 0,84 = 100563

5th = 0,83 = 99366,7

$\boxed{531551{,}37}$ ③

* total launch op. costs

= (L × TFU(launch)) = 4,4386 × 7781,2

= $\boxed{34537{,}6}$ ②

* total PL = L × 35192,6 = $\boxed{156205{,}9}$ ①

* TOTAL COST 5 S/C = 1+2+3+4 = 912432,7

④ $\boxed{190137{,}8}$

‖

−20% ≈ 10^5 #

= 182,5 ~~[illegible]~~

14.3

SMAD
p 665

	KIPS	Data
Command Processing	7	4
Telemetry "	3	2,5
Rate Gyro	9	0,5
Earth sensor	12	0,8
Kinematic integration	15	0,2
Error Determination	12	0,1
Reaction Wheel Control	5	0,3
Complex Ephemeris	4	2,5
Total (KIPS)	67	
+ Complex Autonomy	20	10
Fault detection & correction	5	10
Power management	5	0,5
Thermal control	3	1,5
Total (KIPS)	100	33,1

$K = 2^{10} = 1024 \Rightarrow 100K = 100 \cdot 1024 \times 16$ bits

$= 1\,638\,400$ bits

$= 204\,800$ byte ÷ 8

$= 200$ kB ÷ 1024

$= 0{,}1953$ MB ÷ 1024

SMAD
p 666

Language ADA: $33{,}1\,K = \underline{33\,894{,}4}$

$\Rightarrow \dfrac{33894{,}4}{5} = 6778{,}9$ lines

14.4

① 15 a/c bu
total cost 750 M$

② going to make 25 @ 1125 M$

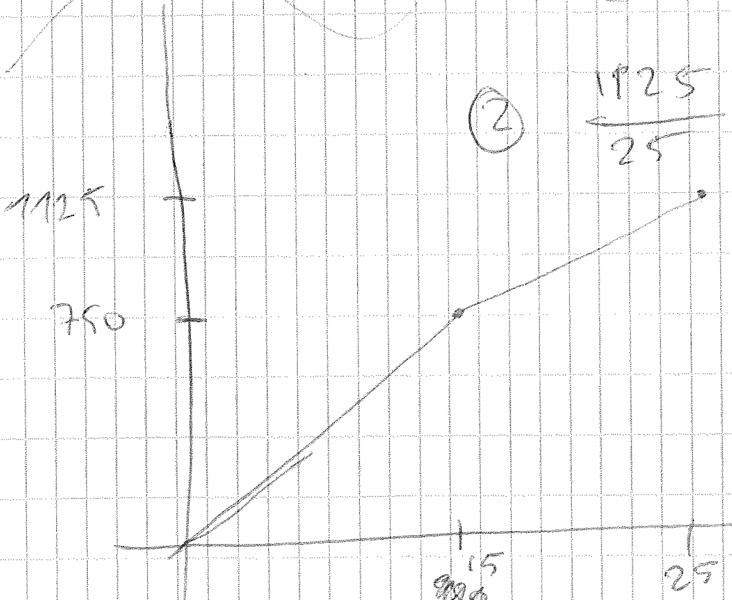
if company has to sell 50 lasses.

? total & average sigle unit cost.

⇒ ① 15 a/c : 1 : $\frac{750\ M\$}{15} = 50\ M\$$

② 10 extra a/c : 1 : $\frac{(1125 - 700)\ M\$}{10} = 37{,}5\ M\$$

② $\frac{1125}{25} = 45\ M\$$



$$UC = TC / N = TFU \times L / N = TFU \times N^{b} / N = TFU \times N^{b-1}$$

$$UC = TFU \times N^{\left(\frac{\ln(S/100\%)}{\ln 2}\right)} = TFU \left(\frac{\ln(S)}{\ln 2}\right) = TFU \times N^{-b}$$

$$50\,M\$ = TFU \times 15^{-b} \quad \wedge \quad 45\,M\$ = TFU \times 25^{-b}$$

$$\frac{50}{45} = \left(\frac{15}{25}\right)^{-b} \Leftrightarrow \ln\left(\frac{50}{45}\right) = \ln\left(\frac{15}{25}\right)^{-b}$$

$$\Leftrightarrow \ln\left(\frac{50}{45}\right) = -b\ln\left(\frac{15}{25}\right)$$

$$\Leftrightarrow -b = -0{,}20626$$

$$\Leftrightarrow \underline{\underline{b = 0{,}20626}}$$

$$TFU = \frac{50M\$}{15^{-0{,}20626}} = 87{,}4\,M\$$$

$$UC(50) = TFU \times 50^{-0{,}20626} = 87{,}4 \times 50^{-0{,}20626}$$

$$= 39M\$$$

$$TC = 50 \times 39\,M\$ = 1950\,M\$$$

14.5

€ 100 M for satellite
=> cost budget for subsystems of s/c payload

=> cost for i&t, system eng, planning, etc...

① cost payload : 0,4 . 100 M euro = €40 M

IR sensor	0,5	241,7 K
visible light sensor	4,5	87,2 K
communications	105 kg	37096,5 K

€ 37,5 M

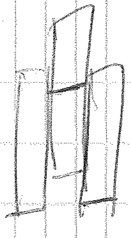
② ~~IA&T : 10,4 × 600 = €6 240 000~~

IA & T = 0,139 . € 100 Miljoen = 13,9 Milj. euro

tabel 20.6

Program Level = 0,229 . 100 milj = 22,9 milj euro
Ground Support Eq = 6,6 milj EUR
LOOS = 6,1 miljoen EUR

14.6 2 core stages
2 boosters



dev. time = 5 year

5000 M euro nominal dev. costs (± 15%) core
1000 M euro (± 10%) booster

Launcher FU = 120 M E
launch oper. cost 30 M E / launch (profit 10M/launch included)

all in 2000 money.

Total operation time for system is 20 year
10 launches / year

annual interest: 6%
S = 85%

a) nominal dev. cost & cost uncert. (%) in 2000 money

?

| 5000 . . .

?

14.7 → payload   cost est. = \$60 mil $SE = 40\%$

s/c → bus   cost est = \$40 mill $SE = 20\%$

? total cost & S_E

36 $\overset{24}{\text{——}}$ 60 —— 84 ⟸ (PL)

32 $\overset{8}{\text{——}}$ 40 —— 48

⇒ total cost = 68   (100)   132

$SE = 32\%$

$TC = 60 + 40 = 100$ M \$

$SE = \sqrt{\sum_i SE_i} = \sqrt{24^2 + 8^2} = \underline{\underline{25,3 \text{ M } \$}}$

or $SE_{s/c} =$ [illegible] $\frac{25,3}{100} = 25,3\,\%$

15. MAIT (Manufacturing, Assembly, Integration & Testing)

{ SMAD : CH 12
SSE : zie B, pg 259
B : vanaf 259

Steps
prepare engineering data
↓
Manufacture components
↓ assembly
Qualify components
↓
Integrate & Test

→ Quality Assurance :
- Management
- configuration management
- Facilities and standards
- control of purchases
- manufacturing control

Test: * Engineering model (EM)
→ when design of a component or subsystem is substanti
different from any existing design.

* Qualification model (QM)
→ built under flight standards under strict quality control
& subjected to full environmental testing

* Flight Model (FM)
→ flight standards / quality control
environmental stresses limited to worst-case flight
values + margin → acceptance MODEL

* Proto-flight model (PFM)
→ flight standards / quality control
qualification tests @ reduced durations

Oefeningen:

15.1

①

prototype	protoflight
→ new designs/missions	→ qualification model is refurbished for flight
→ qualification: representative model	→ qual test progr. applied for half of full test durati
→ one complete additional s/c	→ TFU 1/3 of TFU prototyp
⇒ impact on cost / schedule	→ life of s/c 1,5 times missi life
	→ experience from a number of space project is used.

+ SMAD p 798

② qualification testing — acceptance testing

SMAD p520 + B p 272

if a representative article passes a sequence of qualification tests, all the other articles built to the same data should also pass. In other words, the design is qualified.

We simply have to make sure articles are identical by controlling the engineering data and manufacturing processes. Less severe acceptance tests then certify prop workmanship.

③

Functional Testing	Environmental testing
which item performs what function(s)?	solar radiation, vacuum, mechanical loads, debris, thermal, ...

15.2

What is a verification matrix for?

SSE p575 It identifies how every design and mission requirement, as stated in the specifications, will be verified. The verification is normally by analysis and/or tests.
...

15.3

● What are typical development tests for a space system?

→ static tests
→ dynamic tests
→ thermal tests
→ solar panel tests
→ electric system tests

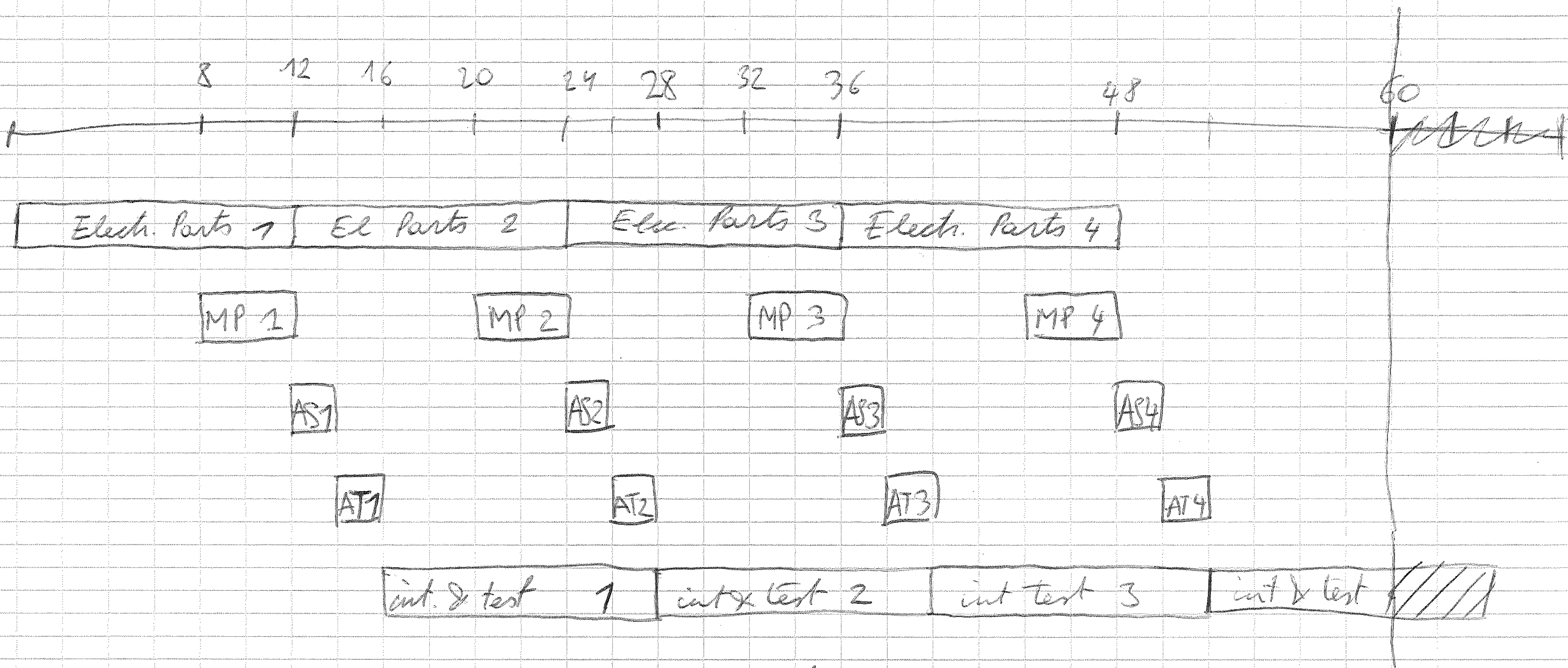
15.4

● MAIT Scheduling for 20 flight-qualified s/c

component manufacture: ① Mech. parts & mat.: 4 months
② elect. parts: 12 months
③ component assembly: 2 months
④ comp. acceptance tests: 2 months
integration ⑤ and test complete s/c: 12 months

? 20 s/c in 60 months without stressing the production capacity

MAIT Scheduling voor 1 lijn



lijn heeft 4 maanden te weinig voor 4 s/c! ⇒ 3 s/c per lijn.

voor 20 s/c : 6 lijnen die 3 s/c maken
1 lijn die 2 s/c maakt.

8 maanden : margin!!