Space II: Workbook Problems

Hoofdstuk 1: Structures

A1: pg 9 → pg 31 Mechanisms → p 38
SMAD: 11.6, 12, 18.3
SSE: 16

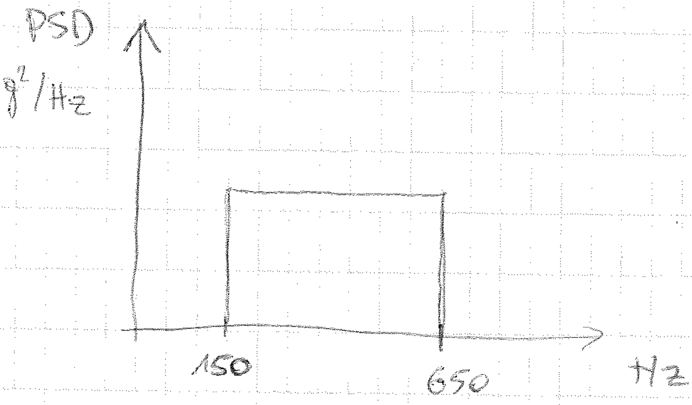
* Environment Requirements
* Mission Requrements
* Launch vehicle requirements
    - ↳ launch loads
    - ↳ natural frequencies
    - ↳ safety

Vragen:

✓ **1.1 Random Loads** pg 16 — Power Spectral Density

gevr: PSD ??

geg: G_{rms} of random acceleration = 10g, PSD is const. between 150 & 650 Hz



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

~~PSD~~

$\Rightarrow$ 500 Hz · PSD = g_{rms}^2

$$\Rightarrow PSD = \frac{100}{500}\frac{g^2}{Hz} = \frac{1}{5}\frac{g^2}{Hz} = 0{,}2\,\frac{g^2}{Hz}$$

1.2 Natural Frequency pg 18

gevr: required wall thickness to meet $f_1 \geq 35$ Hz in axial direction!

gg: cylinder - $L = 5m$, $r = 0{,}5m$ ($D = 1m$)

on top: payload concentrated with a mass of 250 kg → point mass

$E = 70 GPa$

launch load max = 6g (axial acc.)

$(A = opp = 2\pi r^2 + 2\pi r \cdot L)$

opl: $35\,Hz \leq f = \frac{1}{2\pi}\sqrt{\frac{A\,E}{m \cdot L}}$

$\Rightarrow (35\,Hz)^2 \leq \left(\frac{1}{2\pi}\right)^2 \frac{A \cdot E}{m \cdot L}$

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

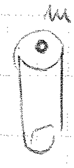
$\Rightarrow A \geq 0{,}00086359\ m^2$

! stel $t = \frac{A}{2\pi r}$ m

$\Rightarrow t \geq \frac{0{,}00086359\ m^2}{2 \cdot \pi \cdot (0{,}5)\ m} = 0{,}000274889\ m \cong 0{,}27\ mm$

✓ 1.3 Tensile Strength p.24_25

gegeven:



$L = 5\,m$

$D = 1\,m \quad (r = 0{,}5)$

$t = 0{,}5\,mm$

$m = 250\,kg$

design loads

$E = 70\,GPa$

$\sigma_{ult.} = 400\,MPa$

QSL : max axial = $-6g$, max lat. = $\pm 1{,}5g$

safety factor : 1,25

gevr: max stress in this cylindrical structure for tensile strength.

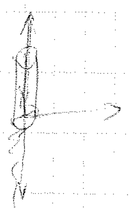
HINTS : 1) Design Loads in x- and y- direction

2) crossectional area & second moment of Area

3) max stress (compression)

① $x:\ m \cdot QSL_{axial} \cdot j = 250 \cdot 6 \overset{9{,}81}{\vee} \cdot 1{,}25 = \underline{18393{,}75\,N}$

$Y:\ m \cdot QSL_{lateral} \cdot j = 250 \cdot (1{,}5 \cdot 9{,}81) \cdot 1{,}25 = \underline{4598{,}4\,N}$



② $A = 2\pi r t = 2 \cdot \pi \cdot 0{,}5 \cdot 0{,}0005\,m^2$
$= 0{,}00157\,m^2$

$I = \pi r^3 t = \pi \cdot (0{,}5)^3 \cdot 0{,}0005\,m^4$
$= 0{,}000196\,m^4$

③ $\sigma_{max} = \dfrac{g_y \cdot M \cdot L \cdot c}{I} + \dfrac{g_x\, M}{A} \leq \sigma_{allowable}$

$\boxed{= 70{,}369\,MPa} \cong 69{,}2\,MPa$!

$= \dfrac{4598{,}4 \cdot 5 \cdot 0{,}5}{0{,}000196} + \dfrac{18393{,}75}{0{,}00157}$

x & y omgekeerd ⇒

g $\dfrac{\cancel{9x}\ \cancel{4} \cdot 5 \cdot 0{,}5 \cdot 4598}{0{,}00157 \cdot 1{,}25} + \dfrac{18393}{0{,}000196 \cdot 1{,}25}$

$= -5857325 + 75073469 = \underline{\underline{69{,}2\,MPa}}$

✓ 1.4 Margin of Safety p. 26

geg: cyl. s/c structure + load from "1.3"
factor of safety for Ultimate load = 1,25

ges: MoS for max compression
judge the design

Lsg:

$$MoS = \frac{\sigma_{allow}}{j \cdot \sigma_{analysis\_designload}} - 1$$

$$= \frac{400\,MPa}{(1{,}25 \cdot 69{,}2\,MPa)} - 1$$

$$= 4{,}62 - 1 = 3{,}62$$

$1{,}5 < MoS < \infty$: Non efficient design that can easily be improved!

1.5 Mechanism Design p.33 zie oplossingenboek!

✓ ## 1.6 Launch and shock Load

launch loads
* QSL = -5,5 g (axial), 1,5 g lateral
* random load spectrum with g_{rms} = 7,5 g
* min natural frequency f of 31 Hz in launch dir.
* Shock response spectrum of your launche shows a high peak at 90 Hz.

first natural frequency of 50 Hz, 2nd close to 90 Hz

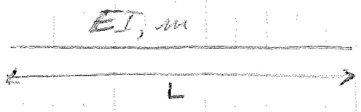
Vragen: 1) primary structure for QSL = -5,5 or G_{rms} = 7,5 g?
2) adaption in the design, what changes?

opl: 1) primary structure always designed for QSL
2) { shock response centrum of high peak @ 90 Hz
{ 2nd natural frequency
⇒ ~~..~~ this will cause severe exitation ⇒ improve design so that 2nd natural frequency lies at 70-80 Hz or above 100 Hz!!

2) $t_d = 1 = 1$ ... = 0,8 M bps

1.7 Solar Array

geg: * 2 wings



EI = bending stiffness

L = solar array wing length = 8 m

m = mass/unit length [kg/m] = 0,8 b kg/m

b = width of the panel [m]

total area of solar array wing is $A = 4\ m^2$

lowest natural frequency of solar array wing $f \geq 0{,}1$ Hz

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

$t = 0{,}25$ mm $= 0{,}00025$ m

$E = 30 \cdot 10^9$ Pa

gevr: h? with $f \geq 0{,}1$ Hz

opl: 1) b? $A = L \cdot b \Rightarrow b = \frac{A}{L} = \frac{4\ m^2}{8\ m} = 0{,}5\ m$

2) m? $m = 0{,}8 \cdot b = 0{,}8 \cdot 0{,}5$ kg/m $= 0{,}4$ kg/m

3) EI? $0{,}1 \leq \frac{0{,}56}{2\pi} \sqrt{\frac{EI}{mL^4}} \Leftrightarrow EI \geq \frac{0{,}1^2 \cdot 4\pi^2}{0{,}56^2} \cdot 0{,}4 \cdot 8^4$

$\Leftrightarrow EI \geq 2062{,}5\ Nm^2$

!! zie dennis 4) steiner's rule $\Rightarrow I = \frac{1}{2} h^2 t b$

5) $I = \frac{EI}{E} = \frac{2062{,}5\ Nm^2}{30 \cdot 10^9} = 6{,}875 \cdot 10^{-8}\ m^4$

6) $h = \sqrt{\frac{2I}{tb}} = \sqrt{\frac{2 \cdot 6{,}875 \cdot 10^{-8}}{0{,}00025 \cdot 0{,}5}} = 0{,}033166\ m = 33{,}16$ mm

2. Thermal Control

[A1 : pg 39 – 58
SMAD : 11.5
SSE : 11 = elf !

* Black body radiation
* absorptivity & emissivity
* heat balance
* radiative heat transfer
* conductive heat transfer
* thermal network analysis

2.1 Earth Flux Density pg 43

~~gg~~: earth is black body with $T = 260\,K$
$R = 6371\,km$

gevr: radiant flux density at 200 km, emitted by the earth.

opl: $\Phi = \frac{E_{tot}}{4\pi D^2} = \frac{4\pi R^2 \sigma T^4}{4\pi D^2} \frac{[W]}{[m^2]} = \frac{6371^2 \cdot 5{,}67 \cdot 10^{-8} \cdot 260^4}{(6371+200)^2}$

$= \underline{\underline{243{,}6\ W/m^2}}$ σ = Boltzmanncte $= 5{,}67 \cdot 10^{-8}\ \frac{W}{m^2K^4}$

2.2 Absorption/Emission SMAD pg 434 zie figuur

1) for the coating : see figure $\Rightarrow \begin{cases} \alpha_s = 0{,}4 \\ \varepsilon = 0{,}6 \end{cases}$

2) ? lage $\frac{\alpha_s}{\varepsilon}$ $\Rightarrow$ lagere temp

2.3 Heat Balance   pg 45 – 46

geg: 2 radiators of A m^2
with * one radiator → sun
* $\frac{\alpha_s}{\varepsilon} = \frac{0,10}{0,80}$
* $S = 1400 W/m^2$
* internal equipment dissipation 165 W

gevr: 1) establish the heat balance of the S/C
2) A = ? met $T_{max} = 33°C$ ($\sigma T^4 = 500 W/m^2$)

opl: $Q_{in} = Q_{out}$

1) $2 \alpha_s^{V} A S$ + dissipation $= 2 \varepsilon 2 A \sigma T^4$

$\Leftrightarrow$ $280 A + 165 = 1600 A$
$\Leftrightarrow$ $1320 A = 165$
$\Leftrightarrow$ $A = \frac{165}{1320} m^2 = 0,125 m^2$

per radiator 2 zijden, dus $A_t = 0,250 m^2$

2.4 Heater System Sizing   pg 46

geg: s/c from 2.3 suffers from a failure case. All equipment is switched off. Heater system → T above $-30°C$

gev: 1) heater power demand to keep $T_{min} \geq -30°C$ ($\sigma T^4 = 200 W/m^2$)
2) if insufficient heater power is available, how could you use the incident Sun on the radiators to keep $T > T_{min}$

1) $\alpha S A + Q = \varepsilon 2 A \sigma T^4$

$$\Leftrightarrow Q = 2 \varepsilon \sigma T^4 A - \alpha S A$$
$$= 2 \cdot 0{,}8 \cdot 200 \cdot 0{,}25 - 0{,}1 \cdot 1400 \cdot 0{,}25$$
$$= 80 - 35 = \underline{\underline{45 W}}$$

2) zwart verwen van "shaded radiator" en in failure mode deze radiator naar de zon draaien.

2.6 Conductions

geg: 1 boom: $T_{avg,boom} = 125°C = 273,15 + 125\,K = 398,15\,K$

$L = 4\,m$

$k = 120\,W/mK$

hollow tube

$\Phi = 20\,mm$, $d = 1\,mm$

boom mounted on a s/c with an avg. temp $T_{s/c} = 25°C = 298,15\,K$

gevr: 1) heat leak: boom <-> s/c, assuming $T_{avg,boom}$ halfway boom

2) why is the uncertainty in the computed heat leak so high.

opl:

1) $C_{ij} = \frac{kA}{L} = \frac{120 \cdot (2\pi \cdot 10 \cdot 10^{-3} \cdot 1 \cdot 10^{-3})}{2} = 3,76 \cdot 10^{-3}$

$Q_{ij} = C_{ij}\,(T_i - T_j) = 3,76 \cdot 10^{-3}\,(100) = \underline{0,376\,W}$

2) the designer doesn't know where the boom has its average temperature.

$\Rightarrow C_{12} = 0{,}002899 \qquad \frac{1}{C_{12}} = \frac{1}{5{,}89 \cdot 10^{3}} + \frac{1}{5{,}7119 \cdot 10^{-3}} = 344{,}85$

2.7 Thermal Shoe Conduction   pg. 43/48

given/assume:

unit 1 mounted on the satellite's platforms
→ has to be thermally insulated, because of a deviating design temperature range.

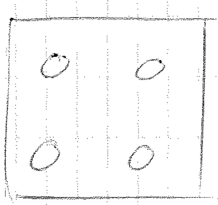
⇒ thermal shoe with parameters:
- unit 1 mounted with 4 feet
- thickness of each foot 4 mm
- thickness of platform 8 mm
- each foot bolted to platform by titanium M4 Bolt ($k = 10$ W/(mK)
- under bolt head and between unit's feet and platform Teflon washers ($k = 0{,}5$ W/mK) are used.
- washer thickness 5 mm
- ↳ $\Phi_{in} = 5$ mm, $\Phi_{out} = 10$ mm

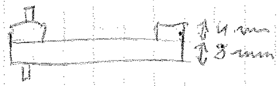
question:

conduction between unit 1 & platform:

$C = \frac{k \cdot A}{L}$

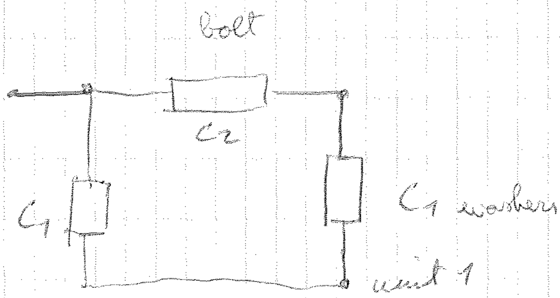
solution:





$$C_1 = \frac{0{,}5 \cdot \frac{\pi}{4}\left(\Phi_{out}^2 - \Phi_{in}^2\right)}{5 \cdot 10^{-3}} = 5{,}89 \cdot 10^{-3}$$

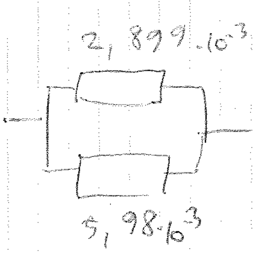
→ platform



$$C_2 = \frac{10 \cdot \pi \cdot (2 \cdot 10^{-3})^2}{22 \cdot 10^{-3}} \text{ ?!}$$

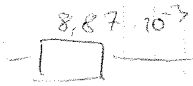
zie boek

$= 5{,}7119 \cdot 10^{-3}$



serie $\left(\frac{1}{C_{12}} = \frac{1}{C_1} + \frac{1}{C_2}\right)$ zie bovenaan

⇒ parallel: $C_{12} = C_1 + C_2 = 2{,}899 \cdot 10^{-3} + 5{,}98 \cdot 10^{-3}$



$= 8{,}87979 \cdot 10^{-3}$

4 poten ⇒ $4 \cdot 8{,}87979 \cdot 10^{-3} = 0{,}0352$

2.8 Transient Behavior   pg 50

given/assume:

$m = 250\ kg$

$h = 750\ km$

4 radiators with area of $1\ m^2$ each.

coated with properties $\frac{\alpha_s}{\varepsilon} = \frac{0{,}15}{0{,}75}$

67 min sunlit phase

4 radiators together absorb

190W solar radiation

30W albedo

240W earthshine

$= 460\ W$ total $- 240W = 220\ W$?

question:

temperature drop during 33 min eclipse

assuming average specific heat of the s/c $c_p \approx 920\ J/kg\ K$

hint: make first-order approximation = linear temp drop

solution:

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

$$\Rightarrow \Delta T' = \frac{\Delta Q\ \cancel{\Delta t}}{m \cdot c_p} = \frac{(\overset{220}{\cancel{460}}) \cdot 67 \cdot 60}{250 \cdot 920} \left[\frac{Ws}{kg \cdot \frac{J}{kg\ K}}\right]$$

$$\Rightarrow \Delta T' = 3{,}845$$

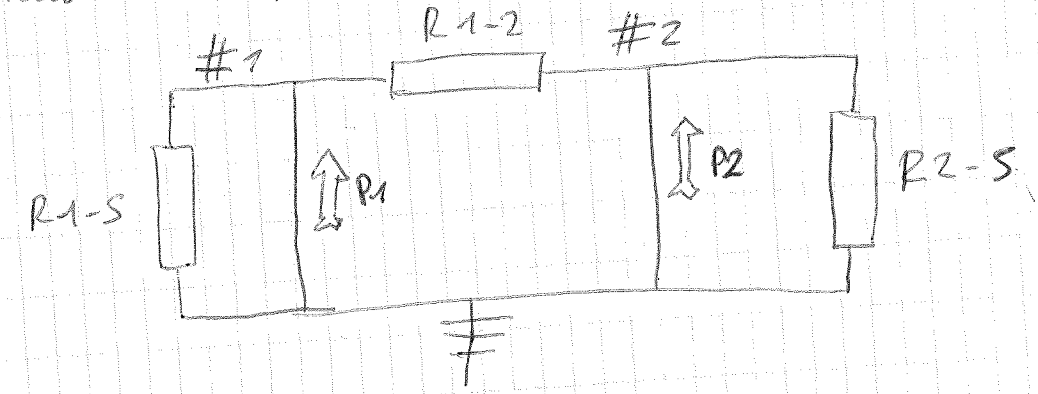
? $$\Rightarrow \Delta T = \frac{3{,}845 \cdot 33}{67} = \underline{\underline{1{,}8939}}$$

$\Rightarrow C_{12} = 0{,}002\,8\ldots$

2.9 Power Source Elimination   pg 50-52

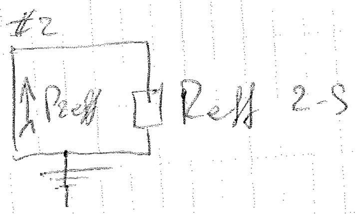
given/assume:
s/c design (thermal) simplified in a 2-nodes network
nodes 1 & 2 : radiator areas → elec. equipment
both rad. face space and dissipate power
both rad. also face each other ⇒ R 1-2

figure:



question:
prove Norton's Theorem for this thermal network (above
which means:
Eliminate #1 and prove that the network above is
equivalent to the network shown here:

where, $P_2^{eff} = P_2 + P_1 \cdot R_{1-2} / (R_{1-2} + R_{1-s})$



$$R_{2-s}^{eff} = R_{2-s} + \left(\frac{1}{R_{1-s}} + \frac{1}{R_{1-2}} \right)^{-1}$$

follow the steps: see pg 46 workbook

solution:

① Establish the equation for Σ Power (#1) = 0

$$P_1 - R_{1-s}\,\sigma T_1^4 - R_{1-2}\,\sigma\left(T_1^4 - T_2^4\right) = 0$$

$$\rightarrow + \left(R_{1-s} + R_{1-2}\right)\sigma T_1^4 = + P_1 + R_{12}\,\sigma T_2^4$$

$$\Rightarrow \sigma T_1^4 = \frac{P_1 + R_{1-2}\,\sigma T_2^4}{\left(R_{1-s} + R_{1-2}\right)}$$

② Express σT_1^4 in P_1 and $T_2^4\sigma$

③ Establish the equation for Σ Power (#2) = 0

$$P_2 - R_{1-2}\,\sigma\left(T_2^4 - T_1^4\right) - R_{2-s}\,\sigma T_2^4 = 0$$

④ substitute expression for σT_1^4. Express σT_2^2 in P_1, P_2 and R

$$P_2 - R_{1-2}\,\sigma T_2^4 - R_{2-s}\,\sigma T_2^4 + \frac{R_{1-2}\cdot P_1}{R_{1-s} + R_{1-2}} + \frac{R_{1-2}^2\,\sigma T_4^2}{R_{1-s} + R_{1}}$$

$$\cancel{\sigma T_2^4 = P_2 + \frac{R_{1-2}\cdot P_1}{R_{1-s} + R_{1-2}}}$$

$$\Rightarrow \sigma T_2^4\left(+R_{1-2} + R_{2-s} - \frac{R_{1-2}^2}{R_{1-s} + R_{1-2}}\right) = P_2 + \frac{P_1\cdot R_{1-2}}{\left(R_{1-s} + R_{1-2}\right)}$$

$$\Rightarrow \sigma T_2^4 = \frac{P_2 + \dfrac{P_1\cdot R_{12}}{\left(R_{1-s} + R_{1-2}\right)}}{R_{1-2} + R_{2-s} - \dfrac{R_{1-2}^2}{\left(R_{1-s} + R_{1-2}\right)}}$$

$$\Rightarrow \sigma T_2^4 = \frac{P_2 + \dfrac{P_1\cdot R_{1-2}}{R_{1-s} + R_{1-2}}}{R_{2-s} + \left(\dfrac{\cancel{R_{1-2}^2} + R_{1-2}R_{1-s} - \cancel{R_{1-2}^2}}{R_{1-s} + R_{1-2}}\right)} = \frac{P_2 + \dfrac{P_1 R_{1-2}}{R_{1-s} + R_{1-2}}}{R_{2-s} + \left(\dfrac{R_{1-2}}{R_{1-s} + R_{1-2}} + \dots\right.}$$

= 0,8 M by...

$$\ldots = \frac{P_2^{new}}{R_{2-3}^{new}}$$

$$\Rightarrow R_{2-3}^{new} = R_{2-3} + \left(\frac{1}{R_{1-3}} + \frac{1}{R_{1-2}}\right)^{-1}$$

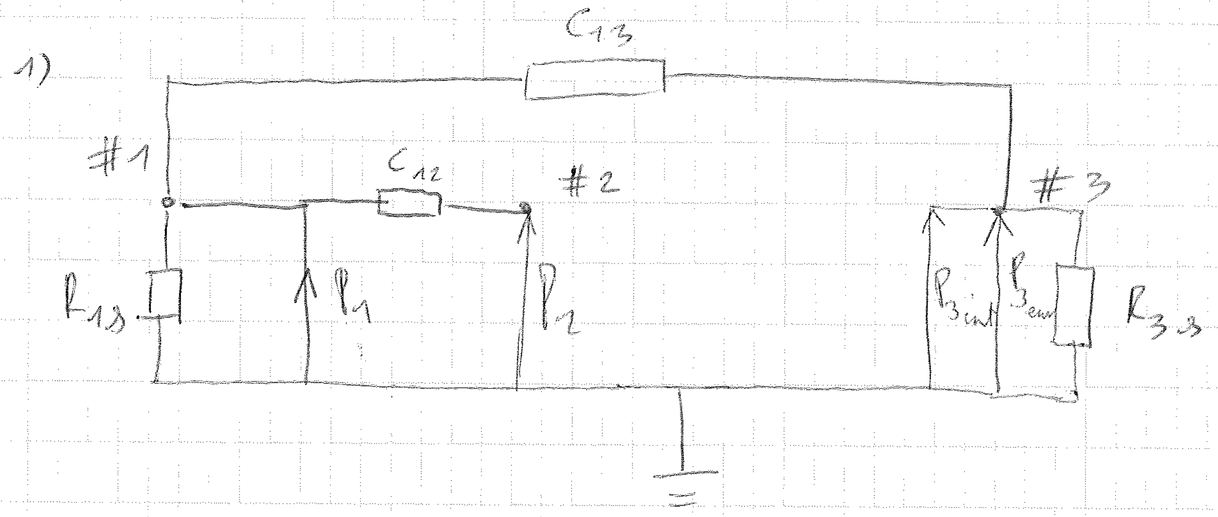
$$P_2^{new} = P_2 + \frac{R_{1-2} \quad P_1}{R_{1-2} + R_{1-3}}$$

2.10 Thermal Network pg 53-57

given see workbook pg 47-48!

question: compute battery temperature and temperature increase when battery dissipates 10% more
use the hints

1)



2) $(\varepsilon A)_{ij} = \dfrac{C_{ij}}{4\sigma T^3}$

$R_{1-2} = \dfrac{1{,}0}{4 \cdot 5{,}67 \cdot 10^{-8} \cdot (293)^3} = 0{,}175\ m^2$

$R_{1-3} = \dfrac{0{,}05}{4 \cdot 5{,}67 \cdot 10^{-8} \cdot 293^3} = 0{,}0088\ m^2$

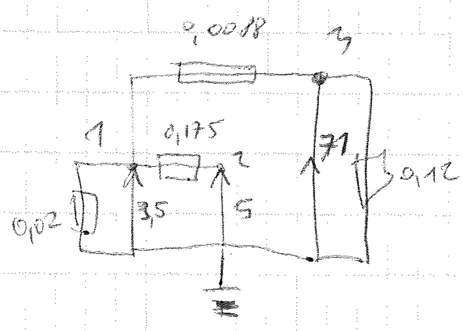
3) $P_1 = 1400 \cdot 0{,}10 \cdot 0{,}025 = 3{,}5\,W$

$P_2 = 5\ W$

$P_3 = 1400 \cdot 0{,}10 \cdot 0{,}150\ \ \overset{+50W}{=} 71\,W$

$R_{1s} = 0{,}80 \cdot 0{,}025 = 0{,}02$

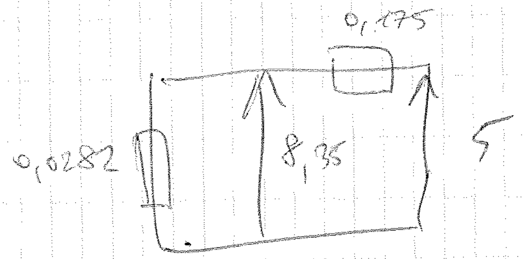
$R_{3s} = 0{,}80 \cdot 0{,}150 = 0{,}12$



4) $P_1^{new} = P_1 + \frac{0{,}0088}{0{,}0088+0{,}12} P_3 = 8{,}35$

$R_{15}^{new} = R_{1-5} + \left(\frac{1}{R_{3-5}} + \frac{1}{R_{1-3}}\right)^{-1} = 0{,}02 + \left(\frac{1}{0{,}12} + \frac{1}{0{,}0088}\right)^{-1}$

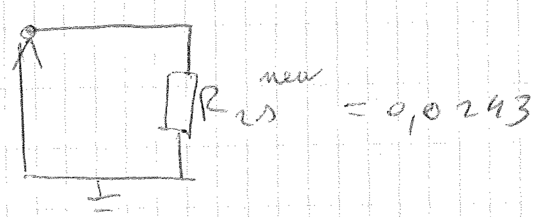
$= 0{,}02 + 8{,}198 \cdot 10^{-3} = \underline{0{,}0282}$



5) $P_2^{new} = P_2 + \frac{0{,}175}{0{,}175+0{,}0282} \cdot \overset{P_3}{8{,}35} = 7{,}191 + 5 = 12{,}191$

$R_{25}^{new} = \left(\frac{1}{0{,}0282} + \frac{1}{0{,}175}\right)^{-1} = 0{,}0243$

6) $P_2^{new} = 12{,}19$



7) $12{,}19 = 0{,}0243\ \sigma T_2^4$ $\qquad P_2 = R_{25}^{new}\ \sigma T_2^4$

$T_2 = \sqrt[4]{\frac{12{,}19}{0{,}0243 \cdot 5{,}67 \cdot 10^{-8}}}$

8) $\frac{dP_2}{dT_2} = 4\, T_2^3\, R_{25}^{new}\, \sigma$

$= 0{,}1589\ \frac{W}{K}$ $\qquad \Rightarrow \frac{dT}{dP} = (0{,}1589)^{-1} \frac{K}{W} = 6{,}3 \frac{K}{W}$

9) $\Delta T_2 = \frac{dT_2}{dP_2} \overset{\approx 0{,}5}{\Delta P_2} = \underline{\underline{3{,}1\,K}}$ $\qquad \left(\frac{dT_2}{dP_2} = \frac{1}{0{,}1589} = 6{,}3 \frac{K}{W}\right)$

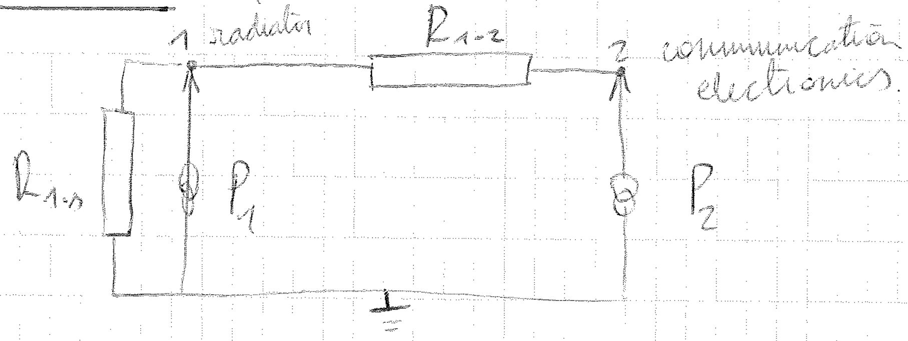
2.11 Iridium Thermal Design

SMAD p 437 tabel 11-44

given see workbook pg 48-49-50

Question 1:

1)



2) $R_{1-s} = \varepsilon A = \varepsilon \cdot \frac{2\pi R \cdot h}{x} = 2{,}0098\ m^2$

$R_{1-s} = \underset{0{,}814}{\varepsilon_{bp}}\ \underset{0{,}5}{\varepsilon}\ 2\pi \underset{0{,}5}{r}\ \underset{1{,}5}{h} = 2{,}05931\ m^2$

3) $P_2 = 250W$

$P_1 = \pi r h \underset{0{,}252\ (\text{white enamel})}{\alpha} S + \varepsilon E \pi r h$

$= \pi r h \,(0{,}252 \cdot 300 + 30 \cdot 0{,}252 + 0{,}8\cancel{33} \cdot 60)$

$= 316{,}53$

4) $P_{2\,max}^{new} = P_2 + \frac{R_{1-2}}{(R_{1-2} + R_{1-s})} P_1 = 250W + \frac{2{,}0098}{(2{,}0098 + 2{,}059)} \cdot 316{,}53$

$= 406{,}35$

$R_2^{new} = \left(\frac{1}{R_{1s}} + \frac{1}{R_{1-2}}\right)^{-1} = 1{,}017\ m^2$

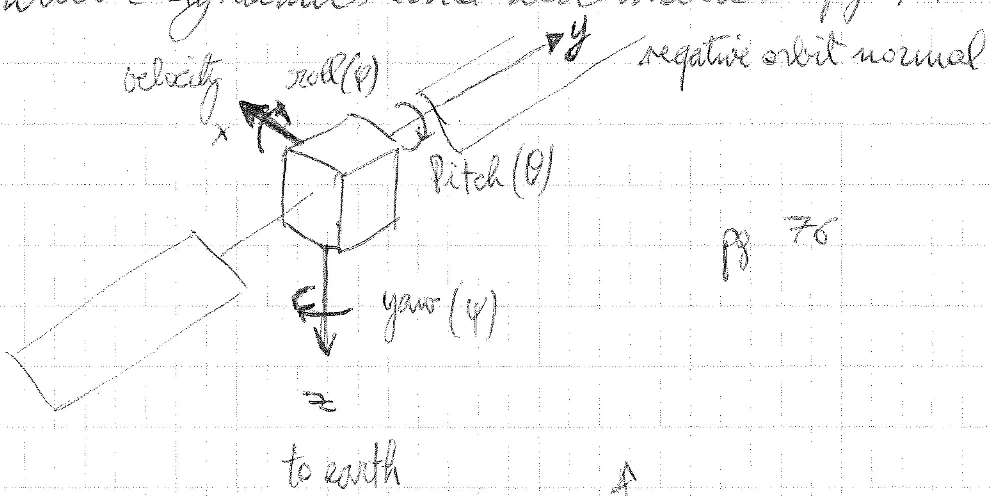
~~4)~~ $\cancel{T_2^{max}}$ $P_2 = R_2 \sigma T^4$

$T = 290{,}4\ K = 17{,}41\ ^\circ C$

5) $T_2^{max} = 30{,}4\ ^\circ C$

Hoofdstuk 3: Attitude and control system (4.1) p59-

* definitions: pg 62
* different s/c attitude concepts pg 68
* impact of mission requirements and other subsystems pg 71
* Design process overview pg 72..
* Attitude dynamics and kinematics pg 74 - 75



pg 76

* Reference Coordinate Frame
* Euler's Dynamic Equations: pg 77 → 79

$$\left.\frac{dH}{dt}\right|_I = \left.\frac{dH}{dt}\right|_B + \omega \times H = M^B$$

where H is the angular momentum vector
ω angular velocity vector
M^B is total internal & external control and disturbance torque vector represented in body fixed reference frame B.

I: ~~abso~~ inertial space I | body fixed frame B.

$H = I\ \omega$

where $$\mathbf{I} = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix}$$ inertia matrix (diagonal elements moments of inertia) (off diagonal elements products of inertia) if principal axes choosen as body fixed ref. frame

$$\Rightarrow \quad \underline{I} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \Rightarrow$$ diag. el. are principal moment of inertia

simplified

$(\overrightarrow{z\ y\ x\ z})$

$$\Rightarrow \quad I_{xx}\,\dot{\omega}_x + (I_{zz} - I_{yy})\,\omega_y\,\omega_z = M_x$$

$$I_{yy}\,\dot{\omega}_y + (I_{xx} - I_{zz})\,\omega_x\,\omega_z = M_y$$

$$I_{zz}\,\dot{\omega}_z + (I_{yy} - I_{xx})\,\omega_x\,\omega_y = M_z$$

$$\omega = [\omega_x \ \ \omega_y \ \ \omega_z]^T$$

$$M = [M_x \ \ M_y \ \ M_z]^T$$

angular vel. are small

1) 3 axis stabilized s/c with no momentum bias $\Rightarrow$ approx when:

$$\Rightarrow \quad I_{xx}\,\dot{\omega}_x = M_x \ ; \quad I_{yy}\,\dot{\omega}_y = M_y \ ; \quad I_{zz}\,\dot{\omega}_z = M_z$$

2) for spinning s/c

$$\Rightarrow \quad I_{xx}\,\dot{\omega}_x + n\,(I_{zz} - I_{yy})\,\omega_y = 0$$

$$I_{yy}\,\dot{\omega}_y + n\,(I_{xx} - I_{zz})\,\omega_x = 0$$

$$(I_{yy} - I_{xx})\,\omega_x\,\omega_y = 0$$

where n is the constant angular velocity component of the spin axis.

3) for nadir pointing 3 axis stabilized s/c in a circular orbit (with ω_0 the angular vel of circ. orbit)

$$\Rightarrow \quad I_{xx}\dot{\omega}_x - (I_{zz} - I_{yy})\,\omega_0\,\omega_z = M_x$$

$$I_{yy}\,\dot{\omega}_y = M_y$$

$$I_{zz} - (I_{yy} - I_{xx})\,\omega_x\,\omega_0 = M_z$$

* Kinematic Equation : see A1 pg 80 → 81

$$\begin{bmatrix}\omega_x\\ \omega_y\\ \omega_z\end{bmatrix} = C(\psi)\,C(\theta)\,C(\phi)\begin{bmatrix}\dot{\phi}\\ 0\\ 0\end{bmatrix} + C(\psi)\,C(\theta)\begin{bmatrix}0\\ \dot{\theta}\\ 0\end{bmatrix} + C(\psi)\begin{bmatrix}0\\ 0\\ \dot{\psi}\end{bmatrix}$$

where

$$C(\phi) = \begin{pmatrix}1 & 0 & 0\\ 0 & \cos\phi & \sin\phi\\ 0 & -\sin\phi & \cos\phi\end{pmatrix};\; C(\theta) = \begin{pmatrix}\cos\theta & 0 & -\sin\theta\\ 0 & 1 & 0\\ \sin\theta & 0 & \cos\theta\end{pmatrix};\; C(\psi) = \begin{pmatrix}\cos\psi & \sin\psi & 0\\ -\sin\psi & \cos\psi & 0\\ 0 & 0 & 1\end{pmatrix}$$

are transform matrices.

K.E. also: $\dot{\phi} = \omega_x + (\omega_y \sin\phi + \omega_z \cos\phi)\tan\theta$

$$\dot{\theta} = \omega_y \cos\phi + \omega_z \sin\phi$$

$$\dot{\psi} = \frac{\omega_y \sin\phi + \omega_z \cos\phi}{\cos\theta}$$

1) simplified, when angles are small $\Rightarrow$ $\dot{\phi} = \omega_x$; $\dot{\theta} = \omega_y$; $\dot{\psi} = \omega_z$
(3 axis-stabilized)

combination of dynamic & kinetic equations:

$$I_{xx}\ddot{\phi} = M_{xx} \;;\; I_{yy}\ddot{\theta} = M_y \;;\; I_{zz} = M_z$$

2) circular orbital velocity ω_0, the K.E.

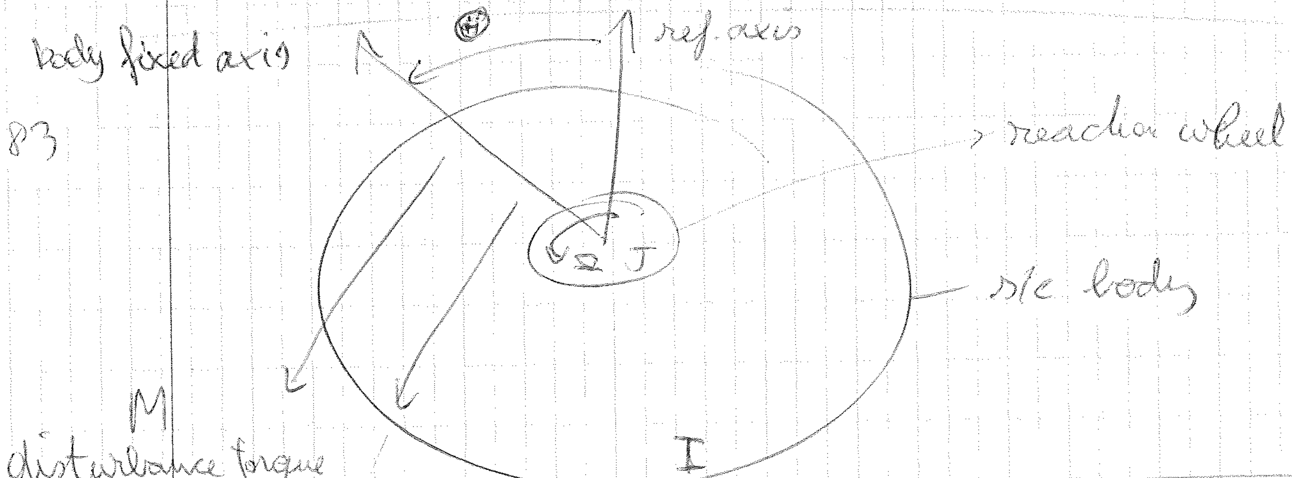
$$\begin{bmatrix} \dot\phi \\ \dot\theta \\ \dot\psi \end{bmatrix} = C^*(\phi,\theta) \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} - C^*(\phi,\theta)\, C(\psi)\, C(\theta)\, C(\phi) \begin{bmatrix} 0 \\ -\omega_0 \\ 0 \end{bmatrix}$$

where $C^*(\phi,\theta) = \begin{bmatrix} 1 & \sin\phi \tan\theta & \cos\phi \tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\theta} \end{bmatrix}$

3) 3 axis stabilized for nadir pointing satellites

$$\begin{bmatrix} \dot\phi \\ \dot\theta \\ \dot\psi \end{bmatrix} = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} \psi\,\omega_0 \\ \omega_0 \\ -\phi\,\omega_0 \end{bmatrix}$$

pg 83



M_c
control torque

$$H_w = J(\dot\Theta + \Omega)$$

$$H_v = I\,\dot\Theta$$

$$\frac{d}{dt}(H_v + H_w) = M$$

$$(I+J)\ddot\Theta + J\dot\Omega = M$$

$$J\dot\Omega = M_c$$

* environmental disturbance torques (pg 84) !
* internal disturbance torques

* Estimating Worst-Case Disturbance Torques

1) Gravity gradient : $M_g = \frac{3\mu}{2R^3} \left| I_{yaw} - I_{min} \right| \sin 2\theta$

$\boxed{pg\ 85}$

2) Solar radiation : $M_a = F\,(c_{ps} - c_g)$

$F = \left[F_s A_s (1+q) \cos i \right] / c$

3) Magnetic field : $M_m = DB$

4) Aerodynamic : $M_a = F\,(c_{ps} - c_g)$
$F = \frac{1}{2}\left[\rho\, C_d\, A V^2 \right]$

* Passive & Active Control

* spin stabilization pg 87

veel meer info

* characteristics of passive control methods pg 93

* Active control pg 96 e.v.

* performance Actuators : pg 101

* example Firesat : pg 112

A.1

Oefeningen:

3.1 General

Def: a) attitude: pg 62
b) attitude determination: pg 62
c) attitude control: pg 62
e) earth observation
f) ~~listed~~ s/c stab. concepts listed pg 68

3.2 Three-Axis Stabilization

a) ~~pg~~ ? pg 71?
b) pg 97 $K_p > 0$ & $K_d > 0$ $\Rightarrow$ stable
pg 98

3.3 Gravity Gradient Stabilization

pg 90 e.v.

given: see workbook pp 51-52

opl a) 1) pitch axis stability: $(I_{xx} - I_{zz}) > 0$

2) roll & yaw axis stability: $3k_x + k_x k_z + 1 > 0$

large - middle $\quad 3k_x + k_x k_z + 1 > 4\sqrt{k_x k_z}$
small

$k_x k_z > 0$ $\quad$ large - small
middle

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

but since above conditions where obtained for I_{yy} largest moment of inertia (I_{zz} in our case) and I_{zz} smallest (I_{xx} in our case)

$\Rightarrow k_x$ & k_z change to

$k_x = \dfrac{I_{zz} - I_{xx}}{I_{yy}}$, $k_z = \dfrac{I_{zz} - I_{yy}}{I_{xx}}$

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

to $I_{yy} - I_{xx} > 0$

substitution: $k_x = 0{,}91016$; $k_z = 0{,}29638$

$3 \cdot 0{,}91 + 0{,}91 \times 0{,}29 + 1 = 4 > 0$

$3 \cdot 0{,}91 + 0{,}91 \times 0{,}29 + 1 = 4 > 2{,}0775 = 4\sqrt{k_x k_z}$

$0{,}2698 > 0$

& $\quad \cancel{7}7465084 - 953159 = 6611925 > 0$

$\Rightarrow$ stable

3.4 Actuator Design: Reaction Wheels

given: workbook pg 52-53

gevr: a) max disturbance torque on s/c pg 85

b) slew torque → slew maneuver in 600 s

→ pg 86

opl: a)

$$M_g = \frac{3\mu}{2R^3} \left| I_{yaw} - I_{min} \right| \sin 2\theta$$

$$= \frac{3 \cdot 3{,}986 \cdot 10^{14}}{2 \cdot ((6371+700) \cdot 10^3)^3} (75-45) \sin(2 \cdot 30°)$$

$$= \underline{4{,}38 \cdot 10^{-5}} \text{ N-m}$$

$$M_{sr} = \frac{F_s A_s (1+q) \cos i}{c} (c_{ps} - c_g)$$

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

$$= \underline{4{,}26 \cdot 10^{-6} \text{ N-m}}$$

$$M_m = D B = \frac{D \, 2M}{R^3} = \frac{1 \cdot 2 \cdot 7{,}96 \cdot 10^{15}}{((6371+700) \cdot 10^3)^3} = \underline{4{,}49 \cdot 10^{-5}}$$

$$M_A = 0{,}5 [\rho \, C_d A V^2] (c_{ps} - c_g)$$

$$= 0{,}5 \left[\rho \cdot 2{,}5 \cdot 1{,}4^2 \cdot V^2 \cdot 0{,}3 \right] = \underline{1{,}13 \cdot 10^{-8}}$$

V^2 & ρ zie SMAD achteraan met altitude 700 km: $\rho_{mean} = 2{,}72 \cdot 10^{-14}$, $V = 7{,}504$ km/s $\Rightarrow$ max $= M_{max} = 4{,}45 \cdot 10^{-5}$

f) $T = \frac{4\theta \cdot I}{t^2} = \frac{4(\frac{\pi}{6}) \cdot 75}{600^2}$ ~~Nm~~ (pg 96)

Hoofdstuk 4: Power System A1

4.1 Energy Source

pg 122

pg 123: $S = 3 \cdot 10^{25} / R^2$
$= 3 \cdot 10^{25} / (149,5 \cdot 10^9)^2$
$= 1342,3 \ W/m^2$

metgeg: $S = 3,8 \cdot 10^{26} / (149,5 \cdot 10^9)^2$
$= 17002 \ W/m^2$

$S_{mars} = 3,8 \cdot 10^{26} / (1,5237 \cdot 149,5 \cdot 10^9)^2 = 7323,2$
$S_{mercury} = 3,8 \cdot 10^{26} / (0,3871 \cdot 149,5 \cdot 10^9)^2 = 113\,469,2$
$S_{pluto} = 3,8 \cdot 10^{26} / (39,5294 \cdot 149,5 \cdot 10^9)^2 = 10,8807$

see table SSE !!

met $3 \cdot 10^{25}$ $\Rightarrow$ $S_{mars} = 3 \cdot 10^{25} / (1,5237 \cdot 149,5 \cdot 10^9)^2$
$= 578,15 \ W/m^2$

$\Rightarrow$ $S_{mercury} = 8957,61 \ W/m^2$
$\Rightarrow$ $S_{pluto} = 0,859 \ W/m^2$

4.2 Solar Array Sizing

a) array power A1 pg 126

X_e / X_d see pg 126

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

where P_e = avg. power during eclipse
T_e = eclipse duration
X_e = total path eff. under eclipse conditions

$$\Rightarrow P_{sa} = \frac{2{,}8 \cdot 10^3 \cdot 69{,}4 / 0{,}65 + 2{,}8 \cdot 10^3 (1436{,}1 - 69{,}4) / 0{,}85}{(1436{,}1 - 69{,}4)}$$

$$= 3513 \text{ W} \approx 3{,}5 \text{ kW}$$

b) life degradation factor pg 129

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

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

$$= 0{,}7374$$

c) Array Size

P_0 amount of solar energy converted into electrical energy / unit solar cell area.

10% cover glass

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

is solar flux

begin of life

$$P_{BOL} = 0{,}77 \cdot 171 \text{ W/m}^2 = 131 \text{ W/m}^2$$

$$P_{EOL} = P_{BOL} \cdot L_d = 131 \cdot 0{,}7374 = 97{,}1 \text{ W/m}^2$$

$$A_{SA} = P_{sa} / P_{EOL} = \frac{3513 \text{ W m}^2}{97{,}1 \text{ W}} = 36{,}18 \text{ m}^2$$

d) ~~number of cells in series (string)~~ pg 130

$n = \frac{V_{SA}}{V_{cell}} = \frac{28\,V}{0,35\,V}$ cell $\Rightarrow$ ~~74 cells~~ 80 cells

e) number of ~~cells~~ parallel strings (series) pg 130

$$\begin{cases} \frac{P_{SA}}{V_{SA}} = I_{SA} = m\, I_{cell} \\ \text{number of cells } N = n\, m \end{cases}$$

number of strings

P_0 multiplied by cell area ($0{,}02 \times 0{,}04\ m^2$)

$\Rightarrow$ 136,8 mW / cell BOL

$\Rightarrow 136{,}8 \cdot 0{,}737 = 100{,}8$ mW per cell EOL

total required EOL: 3513W

$\Rightarrow$ number of cells required is $\frac{3513}{0{,}1008} = 34851{,}8$

$\Rightarrow$ 80 cells in each string $\Rightarrow m = \frac{34851}{80} = 435{,}6 = 436$ strings

4.3 DutSat Battery Sizing

pg 140 e.v.

a) Average power delivered by battery

$$P_{bat} = \frac{300\,W}{0,8} \approx 375\,W$$

Battery voltage should allow a voltage drop of a factor 0,8 over the BDR, while ensuring the bus voltage of 28V.

$$\Rightarrow V_{Bat} = \frac{28\,V}{0,8} = 35\,V$$

b) Peak current (discharge current (I_d)

$$I_d = \frac{P_e}{V_{bus}} = \frac{300\,W}{28\,V} = 10,\cancel{7}\,A$$

c) Number of battery cells

N_{bat} can be estimated from required bus voltage and the voltage delivered by the batt. cells during discharge. $N_{bat} = \frac{35\,V}{1,2\,V} = 29,2$ cells

$\Rightarrow$ 30 cells in series

$V_{bat} = 30 \cdot 1,2 = 36\,V$ during discharge

d) Number of eclipse periods

at most 1 eclipse / orbit.

$\Rightarrow$ maximum eclipses at most the total number of orbits

N_e (max eclipses) over 5 year life: Number of orbits per day times the total number of days per year times number of years

$$N_e = \frac{t_{day}}{t_{orbit}} N_d \cdot N_{yr} = \frac{24 \times 60}{105} \cdot 365 \cdot 5 \simeq 25028 \left| \frac{\text{eclipse period}}{\text{orbits}} \right.$$

e) depth of discharge (DOD) pg 149 A1

NiCd ⇒ DOD of about 20% (22%) see snad 421

⇒ 80% of the total battery charge is left unused

f) Battery energy storage capacity

$$E = \frac{P_{bat} \cdot t_e}{DOD} \quad [Wh]$$

$$= \frac{375 \cdot 35/60}{0{,}2} = 1094\ Wh \approx 1{,}1\ kWh$$

g) Battery Capacity

total required battery capacity (C)

$$C = \frac{E}{V_{bat}} = \frac{1094}{36} = 30{,}4\ Ah$$

h) Total battery mass and volume

$$m_{bat} = \frac{E}{E_{sp}} = \frac{1094}{35} = 31{,}25\ kg$$

SSE 345

$$V_{bat}\ (\text{volume}) = \frac{E}{E_v} = \frac{1094}{95} = 11{,}5\ l$$

avg met E_{sp} of NiCd (30-40 Wh/kg)

E_v of NiCd (80-110 Wh/l)

whole range $\boxed{\begin{array}{c} 27-37\ kg \\ 10-14\ l \end{array}}$

Total weight!

i) time availble for battery charging

$$t_{charge_{max}} = t_d = t_{orbit} - t_{eclipse} = 105 - 35 = 70 \text{ min}$$

j) array power needed for charging ($\eta = 85\%$)

$(P_{SA})_{ch}$ depends on total energy the battery should deliver during discharge. This energy depends on P_e (delivered power), the time (t_e in hours) during which this power is delivered. t_d ($= t_{charge}$) and energy losses in the battery electrical circuitry (η) and the daytime electrical circuitry (η_d).

$$\Rightarrow (P_{SA})_{ch} = \frac{P_{bat} \cdot t_e}{t_d \cdot \eta_d} = \frac{375 \cdot 35/60}{\frac{70}{60} \cdot 0{,}85} = 220 \text{ W}$$

To produce the power necessary for battery charge

$\Rightarrow$ dedicated charge section

because during charge $\rightarrow$ higher voltage

$(28 \times 1{,}5)\text{V} = 42 \text{ V}$ compared to bus volt. of 28V

k) charge current at end of charge

$$I_{ch} = \frac{(P_{sa})_{ch}}{N\, V_{ch}} = \frac{220}{30 \cdot 1{,}5} = 4{,}9 \text{ A}$$

↳ # cells in series!!

N = 27

4.4 Sizing of power subsystem of elec. propelled vehicle

a) <u>solar array area</u> in GEO

$24 \times 60 = 1440$ min

total power required : 1,1 kW + 500 W = 1,6 kW

te_{geo} = 69 min ⇒ compared to an orbital period of 24h

$(P_e = P_d)$

$$P_{sa} = \left(\frac{P_d \times t_d}{X_d} + \frac{P_e \times t_e}{X_e} \right) / t_d$$

$$= \left(\frac{1600\,W \times (1440-69)\,min}{0,85} + \frac{1600\,W \times 69\,min}{0,65} \right) / t_d$$

$t_d = (1440-69)$

$$= 2005\,W$$

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

b) <u>solar array area</u> in parking orbit

total power req. : 1,25 kW + 500 W = 1,75 kW

$(P_e = P_d)$

$$P_{sa} = \left[\frac{1750 \cdot (89-37)}{0,85} + \frac{1750\,(37)}{0,65} \right] \cdot \frac{1}{(89-37)}$$

$$= 3975\,W$$

$$\Rightarrow A_{SA} = \frac{P_{sa}}{P_{BOL}} = \frac{3975}{176}\,m^2 = \underline{\underline{22,6\,m^2}}$$

$$P_{BOL} = \frac{150}{(1-0,02)^8} = 176\,W/m^2$$

c) <u>battery capacity</u>, c (in kWh)

$$C = \frac{P_e \times t_e}{DOD \times eff} = \frac{1750W \cdot 37/60\,h}{0,6 \cdot 0,85} = 2,1\,kWh$$

d) <u>Power regulation (2 methods)</u> used in GEO

PPT (peak power tracking)
SR (shunt regulation
or switching parts of the solar wings)

<u>4.5 Space Shuttle Power System</u>

mass of empty tank: 1800 kg
mass of fuel consumed $= \frac{1}{\eta} \cdot E \cdot M_{fuel\,sp}$

$$\cancel{= \frac{1}{0,5} \cdot 0,6\,kg/kWh \cdot 50\,g/kg}$$

$$= \frac{1}{0,5} \cdot (15kW \cdot 18\,days\,\cancel{x} \cdot 24\,hours) \cdot 0,6\,kg/kWh$$

$= 7776\,kg = 7776$ litres of water

<u>mass of a fuel cell</u> is $\frac{1}{0,5} \cdot \frac{15\,kW}{100\,We/kg} = 300\,kg$

<u>Total mass</u>: $1800\,kg + 7776\,kg + 300\,kg = 9876\,kg$

[illegible] per 60

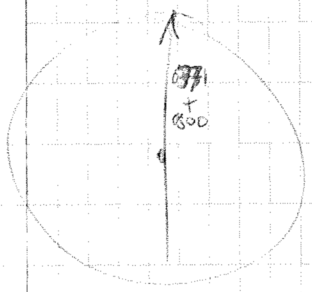
4.6 Iridium Secondary Battery

given: see workbook pg 58

gevr: Calculate mass & volume of the secondary bat.

opl: DOD? → eerst: number of eclipses

$$N_e = \frac{t_{day}}{t_{orbit}} N_d N_y = \frac{24 \cdot 60}{100,8} \cdot 365 \cdot 10 = 52000$$



$$O = 2\pi R$$
$$= 2\pi(6371 + 800)$$
$$= 45056 \text{ km}$$
$$\Rightarrow t_{orbit} = \frac{45056 \text{ km}}{7,452 \text{ km/s}} = 6046,3 \text{ s}$$
$$= 100,8 \text{ min}$$

SMAD

ik lees 17%

$\Rightarrow$ DOD (tabel) $\Rightarrow$ ~~40%~~ NiCd $\Rightarrow$ DOD = 12%

$t_{eclipse} = 35$ min (SMAD last pg)

$P_{bat} = P_e = 620 W$

$$E = \frac{P_{bat} \cdot t_e}{DOD \cdot \eta} = \frac{620 \cdot 35}{0,12 \cdot 0,8 \cdot 60} = 3,8 \text{ kWh}$$

$$M_{bat} = \frac{E}{E_{sp}} = \frac{3,8 \cdot 10^3}{35} = 107 \text{ kg}$$

$$V_{bat} = \frac{E}{E_v} = \frac{3,8 \cdot 10^3}{100} = 38 \text{ l}$$

Hoofdstuk 5: Telecommand & Telecommunications

5.1 Decibels

5.1.1 dB

$E_b = 100\,\mu W$ and $N_0 = 1\,\mu W$. How many decibels is E_b relative to N_0?

antw: Power units are both in μWatts → compatible

$$\Rightarrow 10 \log_{10} \frac{100}{1} = \underline{\underline{20\ dB}}$$

5.1.2 dBi

gain $G = 100$, transmitter power $= 100\,[W]$

How much is the antenna gain, G, compared to an isotropic antenna transmitting the same amount of power in dBi.

$$10 \log_{10} G = 10 \log_{10} \frac{P_{ant.}}{P_{isoch.}} = 10 \log_{10} \left(\frac{PG / 4\pi R^2}{P / 4\pi R^2} \right)$$

$$= \underline{\underline{20\ dBi}}$$

5.1.3 dBW and dBm

$P_A = 1000\,W$. What is the value of, P_A, expressed in dBW and dBm?

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

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

SMAD

5.2 Free Space Loss of a Geo-stationary S/C.

Calculate the free space losses for the C, X, Ku, K and Ka band. Take $h = 36000$ [km.]

a) For the C-band $f = 4 - 8$ GHz:

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

$$\Rightarrow 10 \log_{10} \left(\frac{300 \cdot 10^6}{4 \cdot \pi \cdot 36 \cdot 10^6 \cdot 4 \cdot 10^9}\right)^2 = -195,6 \text{ dB tot } -201,6 \text{ dB}$$

b) / c) / d) / e) idem

met
- X-band: $f = 8 - 12$ GHz
- Ku-band: $f = 12 - 18$ GHz
- K-band: $f = 18 - 26$ GHz
- Ka-band: $f = 26 - 40$ GHz

5.3 EIRP & Flux Density

Given: RF power output $P_t = 100$ [W]
gain $G_t = 30$ [dBi]
Distance between receiver & transmitter $h = 36 \cdot 10^6$ m

a) How much is the EIRP of the transmitter?

A2 P85

$EIRP = P \cdot L_l \cdot G_t$ = effectif isentropic Radiated power
↳ line loss (ground station!!)

$P_t = 20$ dBW $= 10 \log 100$ dBW

$\Rightarrow EIRP = P_t$ [dBW] $+ G_t$ [dBi] $= 20 + 30 = 50$ dBW

b) The flux density on the receiving area:

$$W_f = \frac{P_e G_e}{4 \pi R^2} \left[W/m^2 \right] \qquad EIRP = P_t G_t$$

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

$$= 50 \text{ dBW} - 162{,}12 \text{ dB m}^{-2}$$

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

5.4 Ground Station

given: GS at equator with uplink frequency of $f = 14$ GHz
Earth station RF power $P_e = 1000$ (W)
Earth station antenna diameter $D = 4$ [m]
↳ eff $\eta = 0{,}6$
Antenna Gain of satellite $G_r = 40$ dBi
sat in GEO exactly above GS

a) EIRP of GS?

$$EIRP = P_t \cdot G_t$$

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

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

$$= 10 \log_{10} \left[0{,}6 \left(\frac{\pi \cdot 4 \cdot 14 \cdot 10^9}{300 \cdot 10^6} \right)^2 \right] = \underline{\underline{53{,}15 \text{ dBi}}}$$

$$EIRP = 30 \text{ dBW} + 53{,}2 \text{ dBi} = 83{,}2 \text{ dBW}$$

b) Free Space Loss: , Raakjes !!

$$L_{FS} = \left(\frac{\lambda}{4 \pi R}\right)^2 = \left(\frac{c}{(4 \pi R f)}\right)^2 = 2{,}24 \cdot 10^{-21} = \underline{-206{,}49 \text{ dB}}$$

c) received power at satellite?

$P_{Sr} = EIRP + G_r + L_{FS} = 83{,}2\ dBW + 40\ dBi - 206{,}4\ dB$

dBW $\downarrow$ 10 W $\quad$ $(dBW)\cdot 10^{-1}$

$= -83{,}2\ dBW$

$= 10^{-8{,}32}\ W$

$= \underline{\underline{4{,}78 \cdot 10^{-9}\ W}}$

5.5 Uplink and Downlink Budget

a) Calculate the uplink budget E_b/N_0

A2 pg 8/9

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

pg 10

$$\frac{E_b}{N_0} = \underbrace{P + L_l + G_t + L_{pr} + L_s + L_a + G_r + L_r}_{\text{in dB}}$$

$$+ \underbrace{228{,}6}_{10 \log k = -228{,}6 \frac{dBW}{Hz \cdot K}} - 10 \log \underbrace{T_s}_{\text{in K}} - 10 \log \underbrace{R}_{\text{in bps}}$$

Uplink budget:

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

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

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

Line loss L_l (feeder loss) $= \boxed{-1\ dB}$

Free Space loss: $L_s = \left(\frac{c}{4\pi h f}\right)^2 = 10 \log_{10} \left(\frac{300 \cdot 10^6}{4\pi\, 40 \cdot 10^6 \cdot 18 \cdot 10^9}\right)^2 = \boxed{-209{,}6\ dB}$

Atmospheric loss : L_a $\boxed{-0,5\ dB}$

Earth station at edge, L_{edge} $\boxed{-3\ dB}$

Receiver antenna, G_{rx} = 2500 = $10 \log_{10} 2500$ = $\boxed{34\ dBi}$
system temp, T_s = 290 K = $-10 \log_{10} 290$ = $\boxed{-24,6\ dBK}$

Boltzmann constant, k = $\boxed{+228,6\ \frac{dBK}{Ws}}$

Data Rate, R 10 Mbit/s = $-10 \log_{10} 10^7$ = $\boxed{-70\ dB}$

+

Uplink Budget, E_b/N_0 = $\boxed{38,4\ dB}$

<u>Downlink Budget</u>

Transmitter: $P_t G_t$ = EIRP 23 dBW

Free Space loss: L_s : $10 \log \left(\frac{300 \cdot 10^6}{4\pi \ 40 \cdot 10^6 \cdot 4 \cdot 10^8} \right)^2 = -196,5\ dB$

L_a = $-0,5\ dB$

L_{pr}, pointing loss = $-3\ dB$

Receiver antenna comb. : $G_r = 10 \log_{10} 10^6$ = 60 dBi

system temp: $T_s = -10 \log_{10} 100$ = -20 dBK

Boltzmann cte, k = $+228,6\ \frac{dBK}{Ws}$

Data Rate, R : $-10 \log 10^7$ = -70 dB

+

Downlink Budget, E_b/N_0 = $\boxed{21,6\ dB}$

k) $t_d = 1$ ... = 0,8 M bits

5.6 Noise Temperature

? How much is the system noise temperature?
(given: see workbook)

* effective noise temperature of receiver is:

$$T_{e_{RX}} = T_{LNA} + \frac{T_{MX}}{G_{LNA}} + \frac{T_{IF}}{\cancel{G_{IF}}\ G_{LNA} \cdot G_{MX}}$$

$$= \underline{60\ K} + \frac{850\ K}{\underset{\hookrightarrow 10^5}{50\ dB}} + \frac{400\ K}{10^5\ 10^{-1}} = 60{,}0485\ K$$

* effective noise input at the feeder

$$T_{eF} = T_{ATT}\left(1 - \frac{1}{L_{ATT}}\right) = 290\left(1 - \frac{1}{1{,}122}\right) = \underline{31{,}53\ K}$$

* antenna noise temp @ receiver input:

$$(T_A)_{RX\,in} = \frac{T_A}{L_{ATT}} = \frac{50}{1{,}122} = \underline{44{,}56\ K}$$

antw. * Resulting system noise temperature:

$$T_S = (44{,}6 + 31{,}5 + 60)\ K = \underline{\underline{136{,}1\ K}}$$

→ Resulting Gain of receiver without antenna:

$$G_r = 0{,}5 + 50 - 10 + 300 = 340{,}5\ dB$$

inc. is

→ Figure of merit of this receiver system without antenna gain

$$\frac{G_r}{T_S} = 340{,}5 - 10 \log_{10} 136{,}1 = 319{,}2\ \frac{dB}{K}$$

5.7 Influence of rain on link performance

SMAD p 565

a) How much is the rain attenuation A_{rain}?

aflezen SMAD p 565 : 30 GHz / 99,5% / El. angle 10° $\longrightarrow$ $\pm$ $\underline{\underline{22 dB}}$

b) system noise temp. 1) clear sky
2) rain condition ($T_{rain} = 290K$)

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

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

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

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

1) T_S under clear sky: $$T_S = \frac{T_A}{L_{FRX}} + T_{FRX}\left(1 - \frac{1}{L_{FRX}}\right) + T_{eRX}$$

$$T_S = \frac{28}{10^{0,05}} + \overset{290}{V}\left(1 - \frac{1}{10^{0,05}}\right) + 60 = 116,49\ K = 20,66\ dBK$$

2) T_S under rain condition: $$T_S = \frac{T_A}{L_{FRX}} + T_{FRX}\left(1 - \frac{1}{L_{FRX}}\right) + T_{eRX}$$

$$T_S = \frac{308,2}{10^{0,05}} + 290\left(1 - \frac{1}{10^{0,05}}\right) + 60 = 366,22K = 25,64\ dBK$$

extra: L_{path} | clear sky : $L_{path} = L_{FS} = 206\ dB$

L_{path} | in rain : $L_{path} = L_{FS} + A_{rain} = 206\ dB + 22\ dB = 228\ dB$

geg

$\left(\frac{\lambda}{4\pi}\right)$

5.8 Data Handling, Telecom, Power and Economics

A1
Pg 177

Data Handling

a) 2 important formula's:

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

see table zelfgemaakt

* temp signal data rate: accuracy 1% ⇒ 6 bits.
  10 signals 10 times per second ⇒ 10 × 10 × 6 = 600 bits/sec
* volt sign. 10 × 1 × 9 = 90 bits/s
* exp. sign. 1 × 13 × 200 × 2,2 = 5 720 bits/s

⇒ total bits/s = 6 410 bits/s (= 600 + 90 + 5720)

? b) minimum bandwidth: 6410 Hz

Telecommunication

a) BER ≤ 10^{-7}, which minimal Eb/No can satisfy this req.

BPKS → $\frac{E_b}{N_0}$ for BER = 10^{-5} → 9,6 dB utilisation spectr = 1

⇒ required bandwith = 6410 Hz

b) 11,2 dB = $\frac{E_b}{N_0}$
5,8 dB = $\frac{E_b}{N_0}$

c) SMAD pg 567 last sentence 2 × 6410 bits/s

d) Coding Gain 11,2 − 5,8 = 5,4 dB
this is a factor $10^{0,54} = 3{,}64$
⇒ instead of 30 W transmittion power

e) now 30/3,64 = 8,24 W RF trans power

~~e) power saved~~ " " ⇒ 54 W − 21 W = 33 W

f) output power 30 W & 8,2 W ⇒ 5 − 3,2 hp = 1,8 hp saved

Power System

a) How much mass can be saved by the power system?

→ saving 33W ⇒ saves <u>3,3 kg</u> for the power system
(using the specific power/mass ratio of 10 W/kg)
↳ <u>given</u>

b) 3,3 + 1,8 kg = 5,1 kg total saved

Economics

5,1 × 10 × \$50 000 = \$2 550 000

5.9 Link Budget

given: blzn 63-64

a) What is the signal to noise ratio per bit E_b/N_0?

$$\frac{E_b}{N_0} = 8{,}3\,dB = 10^{0{,}83} = 6{,}76 \approx \underline{6{,}8}$$

b) What is the signal power at the input of the RF receiver amplifier?

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

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

required bit energy, $E_b = 6{,}8\,N_0 = 3{,}5 \cdot 10^{-20}$ Ws

nec. input power $C = E_b R_b = 3{,}5 \cdot 10^{-20} \cdot 6{,}1 \cdot 10^{6} = \underline{2{,}1 \cdot 10^{-13}\,W}$

c) gain of receiver antenna?

$$C = P \cdot L_\ell \cdot G_t \cdot L_a \cdot L_{pr} \cdot G_r \cdot \left(\frac{c}{4\pi h f}\right)^2 = P L_\ell G_t L_s L_a L_{pr} G_r$$

Receiver power C L_ℓ, L_{pr} and L_a are 1 (<u>no losses!</u>)

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

$$\lambda = \frac{c}{f} = \frac{300 \cdot 10^6}{12{,}2 \cdot 10^9} = 2{,}46 \cdot 10^{-2}$$

Receiver antenna gain:

$$G_r = \frac{C}{P\,G_t} \cdot \left(\frac{4\pi h}{\lambda}\right)^2 = \frac{2{,}1 \cdot 10^{-13}}{20 \cdot 10^{2{,}6}} \cdot \left(\frac{4 \cdot \pi \cdot 36 \cdot 10^6}{2{,}46 \cdot 10^{-2}}\right)^2$$

$$= 8919{,}5$$

$$= 10 \log 8919{,}5$$

$$= 39{,}5 \text{ dB}$$

d) effective receiver antenna area?
diameter of the receiver antenna with unaltered BER?

given $\left\{ \begin{array}{l} G_t = 26\,dB \\ \lambda = \frac{c}{f} = 2{,}46 \cdot 10^{-2} \end{array} \right.$

SMAD p 553

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

$$\Rightarrow D_r = \sqrt{\frac{G_r}{\eta}\,\frac{\lambda^2}{\pi^2}} = \sqrt{\frac{8919{,}5}{0{,}8} \cdot \frac{(2{,}46 \cdot 10^{-2})^2}{\pi^2}}$$

$$= \frac{2{,}46 \cdot 10^{-2}}{\pi} \sqrt{\frac{8919{,}5}{0{,}8}}$$

$$= \underline{0{,}8268 \text{ m}}$$

$$A = \frac{G_r}{\eta}\left(\frac{\lambda^2}{4\pi}\right) = \frac{8919{,}5}{0{,}8}\left(\frac{(2{,}46 \cdot 10^{-2})^2}{4\pi}\right) = \underline{0{,}537 \text{ m}^2}$$

Hoofdstuk 6: Propulsion (A.2)

6.1 Requirements

1) propulsion subsystem: def pg 43 / A2 slide 9

2) typical propulsive functions: [see pg 43 / A2 slide 10
solutions pg 29

3) requirements for a propulsion subsystem
pg 45, slide 13

4) $M = 1000\,kg$

$I = M \cdot \Delta V = 1000\,kg \cdot 10^4\,m/s$
$= 10\,000\,000 = 10^7\,Ns$

total impulse

5) idem, when vehicle mass decreases linearly from 1500 kg to 1000 kg with increasing velocity
pg 44 calculate maximum thrust, F for (4), in case
a_{max} should not exceed $10\,g_0$

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

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

$$\Rightarrow I = \int_0 (1500 - 0{,}05\,(V - V_0))\,dV =$$

$$= \left[-0{,}025\,(V - V_0)^2 + 1500\,(V - V_0)\right]_0^{10000} = 1{,}25 \cdot 10^7\,Ns$$

you see: increasing impulse with decreasing mass

6) maximum thrust, F: pg 53 slide 5

$$\begin{cases} F_0 = 1500 \cdot 10g = 147,15 \text{ kN} \\ F_e = 1000 \cdot 10g = 98,100 \text{ kN} \end{cases}$$

↳ thrust varies $\quad I = \int_0^{t_4} F\,dt$ 52

7) min. thrust duration, t_{min} p53 slide 5

$$t_{min} = \frac{\Delta V}{a} \Rightarrow t_{min} = \frac{10000}{10 \cdot 9,80665} \cong 101,97$$

8) Spin-up

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

with $H_O = I_O \cdot \omega \Rightarrow H_{O_1} = 0$ since $\omega_1 = 0$

9?

assuming $r = 2m$ / unif. dist. mass

8 ? →

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

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

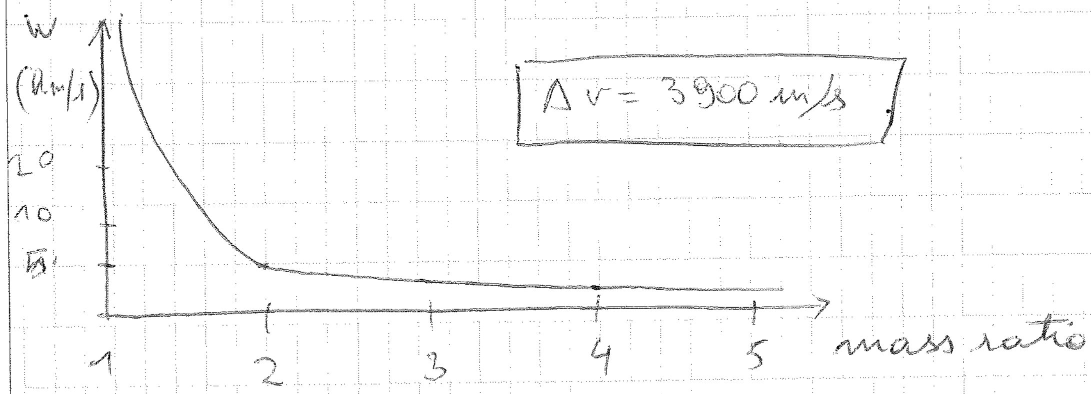
9)

6.2 Rocket Fundamentals

1) $\Delta v = 3,9$ km/s
effective exhaust vel. 3000 - 30000 m/s

graphical relation?

$\Rightarrow \Delta v = w \cdot \ln\left(\frac{M_0}{M_e}\right) \Rightarrow w = \frac{\Delta v}{\ln\left(\frac{M_0}{M_e}\right)}$



2) peripee kick: LEO $\to$ GEO $\quad a_{max} = 1 g_0$
$\Delta v = 3,94$ km/s , $w = 3000$ m/s
M_0?
$M_e = 1100$ kg

a) $\Delta v = w \ln\left(\frac{M_0}{M_e}\right) \Rightarrow M_0 = e^{\left(\frac{\Delta v}{w}\right)} \cdot M_e$

$\Rightarrow M_0 = e^{\frac{3,94 \cdot 10^3}{3000}} \cdot 1100$ kg
$= 4090,4$ kg

$\Rightarrow M_p = M_0 - M_e = (4090,4 - 1100)$ kg
$= \underline{2990,4 \text{ kg}}$

b) $F = cte \Rightarrow F = 1100 \cdot 9,81 = 10,8$ kN
$F = var. \Rightarrow F = 4090,4 \cdot 9,81 = 40,1$ kN

A2 pg 55

c) min operating time from max. thrust!
see solutions pg 32/33

* $\underline{F = cte}$

$$\dot{m} = \frac{10,8 \text{ kN}}{3000 \text{ m/s}} = 3,6 \text{ kg/s}$$

$$t = \frac{2990 \text{ kg}}{3,6 \text{ kg/s}} = \underline{830,6 \text{ s}}$$

* $\underline{F = \text{variable}}$

$$t = \frac{(3940 \text{ m/s})}{(9,80665 \text{ m/s}^2)} = \frac{\Delta V}{a} = \underline{401,8 \text{ s}}$$

A2 pg53 slide 6 56 slide 12

3) <u>total propellant mass</u>

<u>secondary system</u>: $I_{sp} = 150 \text{ s}$

with $I_{sp} = \frac{W}{\underbrace{g_0}_{\approx 10}} \Rightarrow W = 1500 \text{ m/s}$

$$M_0 = 100 \text{kg } e^{70/1500} = 104,78 \quad (\Delta V = 20 + 50 = 70 \text{ m/s})$$

<u>primary system</u>:

with $I_{sp} = \frac{W}{g_0} \Rightarrow W = 3000 \text{ m/s}$

$\Delta V = 75 + 250 = 325 \text{ m/s}$

$M = 104,8$

$$M_0 = M e^{\Delta V / W} = 104,8 \, e^{325/3000} = 116,8 \text{ kg}$$

$M_{fuel} = \underline{16,8 \text{ kg}} = 116,8 \text{kg} - 100 \text{ kg}$

$M_{fuel, sec.} = 4,8 \text{ kg} \qquad M_{fuel, first} = 12 \text{ kg}$

6.3 Chemical Rockets

1) /

2) a) nozzle pressure ratio: pg 65 slide 16 figure

$F = 2{,}5\ kN$

$w = 3000\ m/s$

$\gamma = 1{,}3$

geometric expansion ratio: 100

$\Rightarrow$ figure: $\frac{p_c}{p_e} \approx 2500$

b) exhaust velocity: pg 63 ideal exh. vel sl. 11

$2200°C = 2473{,}15\ K$

$M = 20\ kg/kmol$

$\frac{p_e}{p_c} = \frac{1}{2500}$

$\gamma = 1{,}3$

$\Rightarrow V = 2729\ m/s$

c) throat area:

100 area ratio

$\Rightarrow$ 10 diameter ratio

$\Rightarrow$ nozzle exit: $5\ cm \cdot 10 = 50\ cm = D$

$\Rightarrow A_e = \frac{\pi}{4}(50 \cdot 10^{-2})^2 = 0{,}19635$

$A_{th} = \frac{\pi}{4}(5 \cdot 10^{-2})^2 = 0{,}0019635$

* mass flow: pg 67 slide 19 — 10 bar chamber pressure

$$\dot{m} = \frac{p_c A_t}{c^*} = \frac{1 \cdot 10^6 \cdot 1{,}96 \cdot 10^{-3}}{2240} = 0{,}875 \text{ kg/s}$$

↳ characteristic velocity

* pressure in nozzle exit: $\boxed{\text{pg 65 slide 16}}$

$$\frac{p_c}{p_e} \simeq 2500 \Rightarrow p_e = \frac{10}{2500} = 4 \cdot 10^{-3} \text{ bar}$$
$$= 400 \text{ Pa } [N/m^2]$$

* vacuum thrust: $\boxed{\text{pg 61 slide 8}}$

$$F = \dot{m} \cdot v_e + (p_e - \underset{0 \text{ (vacuum)}}{p_a}) A_e$$

$$= 0{,}875 \cdot 2729 + 400 \cdot 1{,}96 \cdot 10^{-1} = \underline{\underline{2466 \text{ N}}}$$

---

see footnote solutions pg 35

3) a) 1) $\dot{m} = \frac{p_c A_t}{c^*} = \frac{2 \cdot 10^6 \cdot 1{,}96 \cdot 10^{-3}}{2240} = 1{,}753 \text{ kg/s}$

pg 62 slide 9

pressure ratio constant $\Rightarrow$ nozzle exit pressure becomes 800 N/m². $\rightarrow p_e = \frac{20 \cdot 10^5}{2500}$

$$F = \dot{m} \cdot v_e + (p_e - p_a) A_e = 1{,}753 \cdot 2729 + 800 \cdot 1{,}96 \cdot 10^{-1}$$
$$= 4841 \text{ N}$$

$\Rightarrow$ about 2 times the old ~~the~~ thrust.

$$I_{sp} = \frac{w}{g_0} = \frac{v_e + (p_e - p_a)\frac{A_e}{\dot{m}}}{g_0} = \frac{2729 + 800 \frac{1{,}96 \cdot 10^{-1}}{1{,}753}}{9{,}80665}$$

↳ effective exhaust velocity

a)2) zie dennis (7/13)

b) → 20 bar / ideal expansion

2 p ⇒ 2 m maar massaflow = cte

$\Rightarrow m^* = m$ maar $A_{th}^* = \frac{A_{th}}{2}$

$\Rightarrow D_{th} = 3{,}5$ cm → $D_e = 35$ cm (x 10)

$\Rightarrow A_e = 0{,}962 \cdot 10^{-1}$

$F = m \cdot v_e + (p_e - p_a) A_e = 0{,}8\cancel{77}$

pg 55 slide 9 4) $\underline{m} = \frac{F}{W} = \frac{400}{3000} = 0{,}133$ kg/s (req.)

pg 67 slide 19 throat area: $m = \frac{p_c A_t}{c^*} \Rightarrow A_t = \frac{m\, c^*}{p_c}$ ↗ wel

$= \frac{0{,}133 \cdot 1675}{20 \cdot 10^5}$

$= 1{,}11 \cdot 10^{-5}$

$\underline{v} = \sqrt{\frac{2\gamma}{\gamma-1} \cdot \frac{8314{,}32 \cdot T_c}{M} \left(1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right)} = 2985{,}5$

↳ wel 1,23   ↳ 17,4   ↳ pg 65 $= \frac{1}{600}$

pg 61 pressure thrust:

?

~~m w~~

5) Effect on altitude: pg 68 slide 21

$I_{sp} = \frac{w}{g_0} \Rightarrow w = 3922,66$

$\dot{m} = \frac{F}{w} = 127,5 \text{ kg/s}$

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

$w_{vac} = v_e + p_e \frac{A_e}{\dot{m}}$

$w = w_{vac} - \cancel{p_e \frac{A_e}{\dot{m}}} + \cancel{p_e \frac{A_e}{\dot{m}}} - p_a \frac{A_e}{\dot{m}}$

$w = w_{vac} - p_a \frac{A_e}{\dot{m}}$

$\Rightarrow I_{sp} = \frac{w}{g_0} = \frac{w_{vac}}{g_0} - \frac{p_a A_e / \dot{m}}{g_0} = (I_{sp})_{vac} - \frac{p_a A_e}{g_0 \dot{m}}$

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

$F_{vac} = \dot{m} v_e + p_e A_e \Rightarrow F = F_{vac} - p_e A_e + p_e A_e - p_a A_e$

$= F_{vac} - p_a A_e$

At sea level: $I_{sp} = 400 - \frac{1 \cdot 10^5 \cdot 3}{127,46 \cdot 9,80665} = 400 - 240$

$= 160 \text{ s}$

$F = F_{vac} - p_a A_e = 500 \cdot 10^3 - 1,0 \cdot 10^5 \cdot 3 = 200 \text{ kN}$

6.4 Alternative Rocket Propulsion

① Thermal Power

pg 78
slide 13

$P = \dot{m} \cdot c_p \cdot \Delta T = 0{,}34 \cdot 14400 \cdot 2500$
$= 12{,}2$ kW

② Thermal Rocket Design

$F = 16$ kN
$D_{max} = 0{,}3$ m
$I_{sp} = 850$ s
$M = 2$ kg/kmol
$c_p = 1{,}4$
$T = 2500$ K
$p_c = 10$ bar
$c^* = 2175$ m/s

a) $\underline{\dot{m}} = \frac{F}{w} = \frac{F}{I_{sp} \cdot g_0} = 1{,}919$ kg/s

b) beam power = jet power

$P_j = \frac{1}{2} \dot{m} w^2 = \frac{1}{2} F w = 0{,}5 \cdot 16 \cdot 10^3 \left(I_{sp} \cdot g_0 \right) = 66{,}7$ MW

c) throat diameter

$\dot{m} = \frac{p_c A_t}{c^*} \Rightarrow A_t = \frac{\dot{m} c^*}{p_c} = 4{,}176 \cdot 10^{-3}$ m²

$\Rightarrow D_t = 7{,}3$ cm

d) zie dennis $\boxed{9/13}$

③ Electro-Thermal Rocket

dennis $\boxed{11/13}$

④ Nuclear-Thermal Rocket Motor

$F = 35\,kN$
$w = 9\,km/s$
$m = 2000\,kg$
$\eta = 0{,}8$
$T = 3000\,K$

a) Jet Power?

$P_j = \frac{1}{2} \dot{m}\, w^2$ met $F = \dot{m}\, w$ $\left(\dot{m} = \frac{F}{w}\right)$

$\Rightarrow P_j = \frac{1}{2} F w = \frac{1}{2} \cdot 35000 \cdot 9 \cdot 10^3 = 157{,}5 \cdot 10^6\ W$

b) Input Power?

$P_{in} = \frac{P_j}{\eta} = \frac{157{,}5 \cdot 10^6}{0{,}8} = 196{,}875 \cdot 10^6\ W$

c) Specific Power?

$\frac{P_{in}}{m_{prop}} = \frac{196{,}875 \cdot 10^6}{2000} = 98437{,}5\ \frac{W}{kg}$

d) Nozzle area ratio?

$w \approx v_e$

$w = \sqrt{\frac{2\gamma}{\gamma-1} \frac{R_A T}{M} \left[1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]}$

$\Rightarrow 9000^2 = \frac{2 \cdot 1{,}4}{0{,}4} \cdot \frac{8314{,}32 \cdot 3000}{2} \left[1 - \left(\frac{p_e}{p_c}\right)^{\frac{0{,}4}{1{,}4}}\right]$

$\Rightarrow 0{,}927831225 = 1 - \left(\frac{p_e}{p_c}\right)^{0{,}4/1{,}4}$

$\Rightarrow \left(\frac{p_e}{p_c}\right) = \left(1 - 0{,}92..\right)^{\frac{1{,}4}{0{,}4}} = 1{,}009 \cdot 10^{-4}$ fig p65 $\Rightarrow \frac{A_e}{A_t} \approx 140$

(5) Electro-Static Thruster

$F = 25\ mN$

$w = 32\ km/s$

$\eta = 0{,}8$

* $\dot{m} = \frac{F}{w} = \frac{25 \cdot 10^{-3}}{32000} = 7{,}81 \cdot 10^{-7}\ kg/s$

* $\dot{m}(total) = \frac{\dot{m}}{0{,}8} = \frac{7{,}81 \cdot 10^{-7}\ kg/s}{0{,}8} = 9{,}766 \cdot 10^{-7}\ kg/s$

* $P_j = \frac{1}{2} \dot{m} w^2 = \frac{1}{2}\ 7{,}81 \cdot 10^{-7} \cdot (32000)^2$

$= \underline{399{,}9\ W}$

$= \frac{1}{2} \cdot 25 \cdot 10^{3} \cdot 32000$

$= \underline{400\ W}$

* thrust efficiency

Pg 82 slide 21

50% - 70%

* $P_{in} = \frac{P_j}{0{,}5} = 800W$

* Beam Voltage and Current

Zie dennis 13/13

Hoofdstuk 7: Systems Engineering; B 51-61

* space system elements (7)
* Top down and iterative approach → select
* Structured and explicit process
⇒ steps : 1) define problem
2) establish requirements
3) set up options
4) evaluate options
* integrated set of products and process solutions
→ V-figure
flow-down ↓ ⇑ verification ↑ design synth.
* life cycle balanced set of product and process solutions
* interdisciplinary approach

The Process (of systems engineering)
* requirements generation
* set up options
* eval. op
* document & review

7.1 Importance of S.E.

zie solutions

7.2 Basic Engineering Steps

see solutions

7.3 Requirements Generation

solutions

7.4 Analysis Inaccuracy

see solutions
concept 1, 3, 5

7.5 Design Team

communications → all over the world
specialists / functions vital:

pg 57(B) + solutions

Hoofdstuk 8: Mission Concept Exploration B p 1->48

8.1 Mission Elements

see solutions

8.2 Mission Requirements

see solutions

8.3 Space Mission Concept Options

a) Main performance (functional and other) parameters of a satellite-based navigation system.

GPS: - 12 meter ↓, 95% vd tijd
- at any moment 3 sat. (at least) in view from the unknown position
- truly global system
- civil control

SMAD pg 504, 513

rest zie denais!

8.4 Mission Concept

- warmte detector
- foto's
- hoogte meting..

? B pg 85

8.5 Iridium System Trades

~~don't have the article~~ B p291

Hoofdstuk 9: Instrumentation

9.1 Requirements

B, pg 89

9.2 Selection of Observation Wavebands (1)

a) pg 84, B

+ highest resolution — operate only in daylight
— Best resolution is on film

b) pg 84, B

+ Excellent resolution — high power requirem
+ can penetrate below surface — large, expensive system

9.3 Selection of Observation Wavebands (2)

pg 85 B + solutions (heel duidelijk uitgelegd)

9.4 Instrument Resolution

B, p 88 diffraction limit wavelength λ
D aperture diameter

SMAD 264

$$\theta_r = \frac{1{,}22\,\lambda}{D}$$

$$\underset{\|}{0{,}5\,m} \qquad\qquad \underset{\|}{1000\,km}$$

Ground resolution $= 2{,}44\ h\ \lambda/D$

visible $\lambda = 0{,}5\ \mu m$

$$\Rightarrow D = \frac{2{,}44 \cdot 1000 \cdot 10^3 \cdot 0{,}5 \cdot 10^{-6}}{0{,}5} \quad \left[\frac{m^2}{m}\right] = [m]$$

$$= 2{,}44\ m$$

SMAD, pg 265

9.5 Amount of Data

map: scale ⇒ 1 : 25 000

size $1 \times 1\ m^2$

required ground resolution 5 m

goal: min amount of data needed for producing a single map in 8 grey scales ranging from black to white.

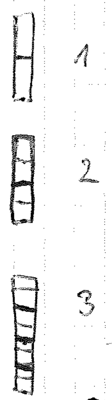
Opl: 1 cm on the map = 250 m

since the map measures 1 m × 1 m

we find that the map coveres 25000 m × 25000 m

for a ground resolution of 5 m (equal to 5000 × 5000 resolution elements)

8 grey scales → 3 bits in digital format



3 × 5000 × 5000 (3 bits / res. elem.) = 75 Mbits

$$\frac{75000000 \text{ bits}}{8} = 9375000 \text{ bytes}$$

$$\frac{9375000 \text{ Bytes}}{1024} = 9155 \text{ kBytes}$$

$$\frac{9155 \text{ kB}}{1024} = 8{,}94 \text{ Mbyte}$$

pg 281 SMAD

9.6 Scanning Mechanism

pushbroom scanning : B pg 106, 105
whiskbroom: B pg 104

verschil zie SMAD p 269

(dis)advantages SMAD p 270

9.7 Instrument Parameters

given
* panchromatic
* circular LEO (800 km)
* 6000 resolution elements
* (min) ground resolution in nadir direction of 15 m
* 10 bit dynamic range

a) Angular resolution

$$\theta_r = 1{,}22\,\lambda / D$$

ground resolution $= 2{,}44\ h\ \lambda / D$

SMAD 265 $15\ m = 2{,}44 \cdot 800 \cdot 10^3\ m\ \ \lambda / D$

stel visible $\Rightarrow \lambda = 0{,}5 \cdot 10^{-6}$

$$\Rightarrow D = \frac{2{,}44 \cdot 800 \cdot 10^3 \cdot 0{,}5 \cdot 10^{-6}}{15\ m}\ m^2 = 0{,}065\ m$$

$$\Rightarrow \theta_r = \frac{1{,}22 \cdot 0{,}5 \cdot 10^{-6}}{0{,}065} = \underline{\underline{0{,}0000094}}\ rad$$

||

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

$$\Rightarrow \theta_r = \frac{X}{2h} = \frac{15}{2 \cdot 800 \cdot 10^3} = \underline{\underline{0{,}000009375}}$$

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

b) Field of view (FOV, in degrees)

?

$$FOV = 2\theta$$

$\hookrightarrow \theta = \arctan \frac{R}{h} =$

B, pg 101

SMAD pg 164

$$FOV = 2\theta = 2 \cdot 9{,}375 \cdot 10^{-6}\ rad$$
$$= 0{,}001074^{\circ}\ (deg)$$

c) Maximum ground resolution cross-track

pg 103 ?? $Z_c = 6000$

d) Data Rate per second

B pg 112

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

Z_a = number of lines read / second along track

$$Z_a = \frac{V_N}{Y} = \frac{3{,}564\ deg/min \cdot 6378{,}14\ km}{15} = \frac{6622\ m/s}{15\ m}$$

$\hookrightarrow$ ground track velocity $= 442$

$$\left[\frac{deg}{min}\right] \cdot [km] = \times \frac{1}{60} \cdot \frac{180}{\pi} \left[\frac{rad}{s}\right] \cdot 10^3\ [m]$$

$$\left(\frac{deg}{min}\right)[km] = \times \frac{1}{60} \times \frac{2\pi}{360} \times 10^3 \left[\frac{rad}{s}\right][m]$$

Number of pixels across track is identical to the number of resolution elements (given)

$Z_c = 6000$

$$\frac{\ldots}{1024} = 8{,}94\ \text{Mbyte}$$

Dynamic range, B = 10 bits / pixel

Number of bands observed : $1 = N_c$ (panchromatic)

$$DR = Z_a \cdot Z_c \cdot B \cdot N_c = 442 \cdot 6000 \cdot 10 \cdot 1$$
$$= 26\,520\,000 \text{ bits/s}$$
$$= 26{,}5 \text{ Mbps}$$

e) <u>pixel dwell time</u>

1) <u>push broom scanning</u>

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

2) <u>whiskbroom scanning</u>

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

9.8 Instrument Parameters (2)

idem, but @ 12 km
velocity of 200 m/s

arctg

a) $\theta_a = \frac{X}{2h} = \frac{15 \text{ m}}{24000 \text{ m}} = 0{,}000625$

$\times 360 / 2\pi$

b) $FOV = 2\theta = 0{,}00125$ ~~rad~~ deg

rad → deg

c) Max GRCT ?

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

e) $t_d = \frac{1}{Z_a} = \frac{1}{\ldots} = 0{,}075$ s/line ... 0,0000125

9.9 Multi - Colour Imager

* field of view
* aperture size
* focal length
* data rate

* $IFOV = 2\theta = 2 \arctan \frac{7,5}{800 \cdot 10^3} = 0,00107$

* focal length, $f = \frac{h \cdot d}{X} = \frac{800 \cdot 10^3 \cdot 15 \cdot 10^{-6} \, m^2}{15 \, m}$

$= \underline{0,8 \, m}$

? * N_m = number of pixels $= 4 \times 64 = 256$

* $D = \frac{2,44 \lambda \cdot f \cdot Q}{d} = \frac{2,44 \cdot 1 \cdot \cancel{10^{-6}} \cdot 0,8 \cdot 1}{15 \cdot \cancel{10^{-6}}}$

$= \underline{0,13 \, m}$

* $F\# = f / D = 6,15$

* Field of view $= FOV = IFOV \cdot N_m = 0,00107 \cdot 256$
$= 0,27392$ deg

*

zie SMAD p288

7

9.10 Instrument Size Mass and Power Estimation

* tabel 9.13 SMAD
characteristics of Typical Payloads

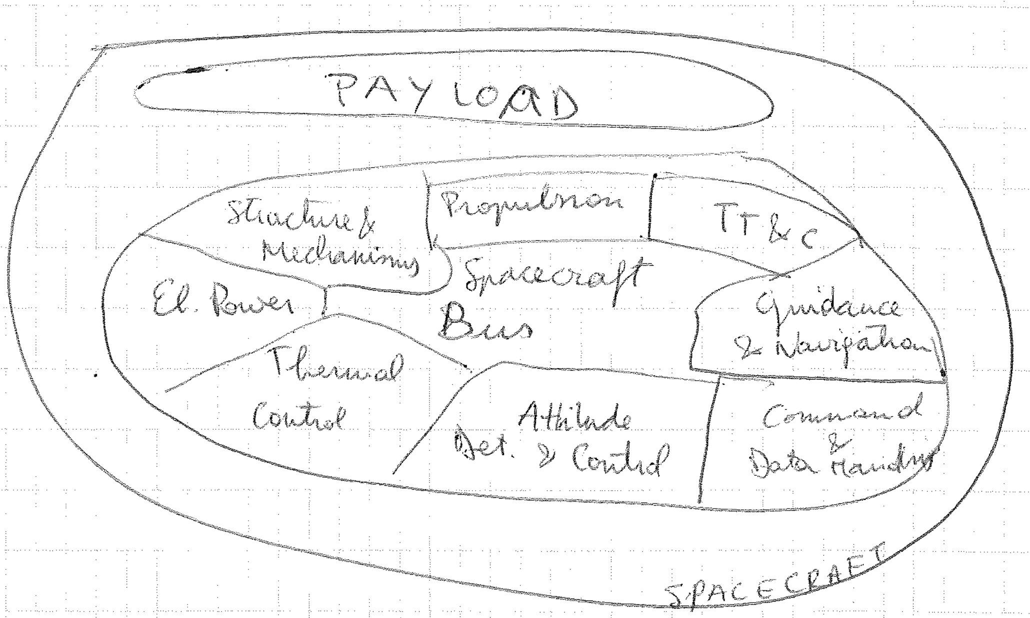
As reference instrument we select the Solar Optical Telescope

$\left\{\begin{array}{l}\text{Aperture diameter } 1{,}25\,m\text{, mass } 6600\,kg\text{, power } 2\,kW \\ \text{and size } 7{,}3 \times 3{,}8\,m \text{ diameter}\end{array}\right.$

$\Rightarrow$ volume $= 7{,}3 \times 1{,}9^2 \times \pi = 82{,}79\,m^2$

Hoofdstuk 10 : Bus De...g.. B p 121 - 156

10.1 Spacecraft bus subsystems



uitleg functies : zie AE1-801 : part 1
zie pg 129, B

10.2 Main Bus Functions Mars Observer

? waar vind ik dat artikel?

10.3 Spacecraft Mass * Budgetting * Estimation and

1) vehicle dry mass

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

$\Rightarrow \Lambda = e^{\frac{535}{2950}} = 1{,}199$

total vehicle mass $= 690 = M_0 \Rightarrow \frac{M_0}{M_e} = 1{,}199$

$\Rightarrow m_e = \frac{690}{1{,}199} = 575{,}5$ kg

2) payload mass:

mass FM channels + mass antennas
= 120 kg + 40.3 kg
= 240 kg

3) S/C bus subsystems

575,5 − 240 = 335,5 kg for the S/C bus subsys.

verder: zie solutions

10.4 Data used for Mass Estimation and Budgetting

small micro satellite 50 - 100 kg

gevr: 4 comparable spacecrafts
→ avg $\frac{\text{payload mass}}{\text{dry mass}}$ ratio

→ (dry) mass distribution over various vehicle subsystems

opl: SMAD pg 854-855
874
$\boxed{\text{p 895 - 896}}$
hier vind je de verschillende massa's en dus ook 4 comparable spacecraft

1) Bremsat, 68 kg,
2) orbcomm FM1 47 kg
3) Posat 1, 50 kg
4) Ørsted

ook data van dictaat

10.5 Propellant Mass Estimation and Budgetting

Δv budget:

Apogee kick : 1,8 km/s
Station keeping : 15 x 55 m/s = 825 m/s
Momentum wheel unloading : 15 x 6 m/s = 90 m/s
End of life disposal (assumption) : 100 m/s

* Selecting a dry mass of 3000 kg, we find that the propellant required by the monopropellant hydrazine system is:

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

$$\Rightarrow M_0 = 3000\ kg \cdot e^{\left(\frac{1015}{2000}\right)}$$

$$= 4983,3995\ kg$$

$\Rightarrow$ hydrazine propellant mass $\cong$ 1983 kg

Propellant mass needed for apogee kick motor:

$$M_0 = 4983,4 \cdot e^{\left(\frac{1800}{3000}\right)} = 9080,3\ kg$$

* Selecting a dry mass of 2000 kg

$\Rightarrow$ hydr. prop. mass of 1306 kg
$\Rightarrow$ kick motor prop. mass of 2718 kg

!! Total vehicle mass over 6000 kg
Proton M is not suited for the mission we are considering!

10.6 Power Estimation & Budgetting

? same bus as in 10.3
input power 6.0 kW

10.7 Spacecraft Mass and Size Properties Estimation

? * estim. mass of the vehicle 2572 kg
* max. power need from solar panels 1900 W
* distance from sun 1,35 AE

↳ solar flux mitrehnen.

Hoofd. 11 Launch Vehicle Selection B p 157 - 184

@ minimum cost & risk

availability: $A = 1 - \left[L (1-R) T_d / \left(1 - \frac{1}{S}\right)\right]$

with: L = nominal number of flights a year
R = success rate (0,8 - 0,98)
S = surge rate (1 → 1,5)
T_d = stand down time following from a failure in years
(1/3 - 2,5 year)

11.1 Launcher Availability zie solutions

which ~~spacecr~~ launcher has the highest availability

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

$= 0,36$

Launcher 2: $A = 1 - \left[20(1-0,93) \cdot \frac{1}{3} / \left(1 - \frac{1}{2}\right)\right]$

$= 0,067$

⇒ Launcher 1 has 36% availability, where Launcher 2 has only 6,7%

11.2 Launcher Selection (1)

see B pg 165 - 166
dedicated ⇒ specific launch?

11.3 Launcher Selection (2)

200 kg in orbit → 2 launcher → select!

ex: for 7,7% more cost = 1M $

we get 9% more reliability

⇒ choose launcher 2! (maybe sell the other 100 kg.)

11. 4 Parameters of Importance for Launcher Selection

list the parameters of importance for launcher selection

see solutions pg 66

Hoofdstuk 12 : , : Assessment B p215 - 228

12.1 Risk Assesment Background (see solutions)

* **What is risk?**

(def) The potential for realization of **unwanted**, adverse consequences to human life, health, property, or the environment

* **What is risk assessment**

The process of establishing information regarding acceptance levels of a risk and/or levels of risk for an individual, group, society or the environment

Why: x risk assessment is necessary to ensure mission succes and to prevent technical problems as well as the associated cost and schedule overruns.

12.2 Risk Analysis Process

see solutions P8 67

12.3 Risk Identification

? 1) no

? 2) aantal reserve capaciteit.
~~aan dat je bepaalde~~

12. 4 Quantifying Technology Development Risks

from scratch

geg: total budget available 4,2 M \$.

estimation of cost of development of the component 4 M \$

excluding technology development risks.

gevr: estimate techn. devel. risk

opl: TRL, based on "no prior experience"

⇒ TRL of 1 ⇒ standard deviation about the most likely estimate of 25% or more!

$\sqrt{0{,}25^2 + 0{,}12^2} \approx 0{,}28$

?! Together with the cost estimating uncertainty of 0,5 M \$

⇒ total uncertainty of ~ 28%

⇒ probability of cost of development being higher than the available budget cannot be neglected.

12.5 Visualization of High Risk Items

what is a risk matrix?

6, p 226?

? where?

12.6 Risk Mitigation

? zie vragen werkboek

Hoofdstuk 3 : Reliability ; B pg 229

Mean Time To Failure (MTTF) $= \frac{1}{\lambda}$ → hazard rate

met $y = e^{-\lambda t} = Rt$
$\ln y = -\lambda t$

Reliability modes : series, parallel, combination

$R = \pi R_i$; $R = 1 - \pi(1 - R_i)$; (X)

$$R = \sum_{r=k}^{n} \binom{n}{r} \cdot R^r \; (1-R)^{n-k}$$

with $\binom{n}{k} = \frac{n!}{k! \, (n-k)!}$

13.1 Reliability Estimate

gg: operational life of 1 year / MTTF of 1,5 year

gevr: Hazard rate; reliability, rel. in case oper. life is ext. to 2 year

opl: * $\lambda = \frac{1}{MTTF} = \frac{1}{1,5} \cong 0,67$ failures/year ← Hazard rate

* Reliability with 1 year op. life : $R = e^{-\lambda t} = e^{(-0,67 \cdot 1 year)} = 0,512$
  this is a reliability of 51,2 %

* $R = e^{-\lambda t} = e^{(-0,67 \cdot 2)} = 0,262$ of 26,2%

13.2 Reliability Modelling

Soyuz : 3 core stages (1 lower, 2 upper stages)
4 parallel staged rocket boosters.

? reliability of single rocket booster:

* success rate soyuz : 96,8%
* reliability 2 upper stages 0,998
* rel. of lower core stage is identical to single rocket booster

opl. $R[\text{launcher}] = R(\text{core } 1) \times R(\text{core } 2) \times R(\text{core } 3) \times R(\text{booster } 1) \times R(\text{booster}$

$$R[\text{launcher}] = R[\text{upper}]^2 \times R[\text{unknown}]^3$$

$$0{,}968 = (0{,}998)^2 \times R[\text{unknown}]^3$$

$$\Leftrightarrow \sqrt[3]{\frac{0{,}968}{(0{,}998)^2}} = R[\text{unknown}] = 0{,}991$$

?

13.3 Reliability Modelling (2)

2 latching valves each : 0,99
2 sets of thrusters : 0,98

$\Rightarrow R = (0{,}99)^2 \times (0{,}98)^2 = 0{,}94$

$$\left.\begin{aligned} R_1 &= (0{,}98)^4 \times (0{,}99)^2 = 0{,}904 \\ R_2 &= (0{,}98)^2 \times (0{,}99)^2 = 0{,}941 \end{aligned}\right\} \quad R_1 \cdot R_2 = R = \underline{\underline{0{,}851}}$$

13.4 Reliability Modelling (3)

geg: 16 active transponders + 4 backup transponders ...
Each transponder has a MTTF of 100.000 hours.

gevr: reliability of a single transponder
overall payload reliability when mission duration is 5 years

opl: $R = e^{-\lambda} = e^{-\frac{1}{100000} \cdot 5 \cdot 365 \cdot 24} = 0{,}6453$

$\binom{n}{k} = \frac{n!}{k!\,(n-k)!}$

$\frac{20!}{16!\,4!}$

$$\begin{aligned} R = &\binom{20}{16} 0{,}645^{16} \cdot (1-0{,}645)^{20-16} + \\ &\binom{20}{17} 0{,}645^{17} \cdot (1-0{,}645)^{20-17} + \\ &\binom{20}{18} 0{,}645^{18} \cdot (1-0{,}645)^{20-18} + \\ &\binom{20}{19} 0{,}645^{19} \cdot (1-0{,}645)^{20-19} + \\ &\binom{20}{20} 0{,}645^{20} \cdot (1-0{,}645)^{20-20} \\ = &\ 0{,}069 + 0{,}045 + 0{,}018 + 0{,}002 + 0{,}0 = 0{,}134 \end{aligned}$$

13,4% =

13.5 Space Shuttle Fuel Cell System Reliability

hoe?!

a) $R = e^{-\lambda t} = e^{-\lambda \cdot 2} = 0{,}9983$

$\downarrow$

$\lambda = 8{,}507 \cdot 10^{-4} \; = -\frac{1}{2} \ln 0{,}9983$

$R = e^{-\lambda t} = e^{-8{,}507 \cdot 10^{-4} \cdot 18} = 0{,}985$

$\Rightarrow$ 98,5% reliability

b) $R = 0{,}985^4 + \binom{4}{3} 0{,}985^3 (1 - 0{,}985)$

$= 94{,}06\,\% + 5{,}8\,\% = 99{,}86\%$

c) $R = 1 - (1 - 0{,}996)^N$ with $R \geq 0{,}99999$

hoe?

$\Rightarrow N$ (number of groups) $= 2$ with a total reliability of $0{,}999998$

d) MTBM is based on MTBF.

from (a) we know that the failure rate $\lambda = 8{,}5072 \cdot 10^{-4}$ failures/day

$\Rightarrow \text{MTBF} = \frac{1}{\lambda} = 1175$ days

Based on this result we select a MTBM < MTBF, but not too small as the maintanance costs will become very high.

13.6 Reliability Budgetting

→ total bus reliability → 0,80

(a) assuming all subsystems contribute equally to total (bus) reliab.

(b) based on failure data given

opl: assuming that all bus subsystems work independently from each other and that all subsystem failures will lead to a bus failure (no redundancy between different subsystems)

a) ⇒ subsystems reliability should be equal to $0,8^{1/7} = 0,968$

b) taking an arbitrary lifetime of 1 year
⇒ overall failure rate:

$R = e^{-\lambda t}$, $R = 0,8$, $t = 1$

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

of this failures, 33,6% is attributed to the communications subsystem indicating a failure rate of $0,336 \cdot 0,223 = 0,075$

this gives a reliability over the earlier assumed lifetime of 1 year of $R = e^{-0,075} = 0,9277$

⇒ for the other subsystems:

		failrate	Reliability
Guidance & nav	18,6%	0,0415	0,9593
El. power	18%		
C & DH	12,4%		
Thermal	7,6%		
Propulsion	5%		
Structure	4,8%		
Total			$x \cdot x \cdots = 0,8$

13.7 Qualification Test Programme

geg: operational life 100.000 hours
component reliability of 0,999 9
confidence level 95 %
no failures during test
overall test duration half a year

gevr: effect of number of test failures on the test programme and if it's reasonable to this component to allow at least 1 failure to occur?

opl: ? MTTF

$$R = e^{-\lambda t} = e^{(-\lambda \cdot 100\,000\ h)} = 0{,}999$$

$$\Rightarrow \lambda = \frac{1}{100\,000}(-\ln 0{,}999) = 1 \cdot 10^{-8} \text{ failures/hour}$$

$$\text{or MTTF} = \frac{1}{\lambda} = \frac{1}{10^{-8}} = 10^{8} \text{ hours} = 100 \text{ million hours}$$

~~Hoe??~~

To confirm 100 million hour MTTF objective @ 95% confidence allowing no fails ⇒ test length must be 300 mill. hours (see confidence level)

1 year = 8760 hours ⇒ 1 single item testing for 34000 years or 64000 items for 0,5 year

* in case of test failures ⇒ test length → lengthened
or more items to be tested

allowing 1 failure → ± factor 2
but then the test is fairer to the supplier

<u>14   ing</u> B p 187 - 214 | SMAD p 795 e.v
→ tabellekes!

14.1 Cost Estimate

→ waar kan je dit vinden?!

14.2 Space Segment Cost

geg: telecommunication mission:
5 identical comm. sat. / payload mass 360 (335 kg elech. / 25 kg antennas)
dry mass of sat. bus (excl. payl.) ↳ 1228 kg (incl. 85 kg AKM)

gevr: total space segment cost? (estimate) with learning curve slope 0,95

opl: assume prototype approach

{ s/c bus dry mass = 1228 kg
{ s/c bus + payload dry mass 1588 kg

tabel: RDT&E cost   sum = 251216

1	payload: communications:	$353,3 \cdot 360\ kg$	$= 127188$
2	s/c bus	$101 \times 1228\ kg$	$= 124028$
3	IAT (s/c + bus)	$989 + 0,215 \cdot \cancel{1588}$ $(127188 + 124028)$	$= 55000,44$
4	Program level ↳	$1,963\ (251216)^{0,841}$	$= 68290,47$
5	GSE	$9,262\ (251216)^{0,642}$	$= 27135,33$
	Total		$401641,77$

total RDT&E costs are estimated at 401,6 M \$. Commercial program $\Rightarrow$ reduce our estimate with 20% leaving a total RDT&E cost of 321,3 M \$ 5

TFU cost : tabel 20.5 pg 796 SMAD

payload	$140 \cdot 360$ =	50400
s/c	$43 \cdot 1228$ =	52 804
totaal		103204
IAT	$10,4 \cdot$ (~~103204~~ 1588) =	16515,2
PL	$0,341 \cdot 103204$ =	35192,6
2005	$4,9 \cdot 1588$ =	7781,2
Totaal	+	= 162693

~~$\Rightarrow$ first unit cost $\approx$ 162,7 M \$ $\Rightarrow$ 20%~~

1 s/c TFU : payl. + s/c + IAT = 119719 4

SMAD 810

2nd unit	:	(~~0,88~~ ~~0,78~~ 0,90) $\times$ 1	= 107747
3th "	:	$0,87 \cdot 119719$	= 104156
4th "	:	$0,84 \cdot 119719$	= 100564
5th "	:	$0,83 \cdot 119719$	= 99367
~~totaal:~~			411 834 3

total launch operations cost :

$(1 + 0,9 + 0,87 + 0,84 + 0,83) \cdot 7781,2 = 34548,5$ 2

total program level ~~[illegible]~~ costs : $(1 + 0,9 + 0,87 + 0,84 + 0,83) \cdot 35192,6$

$= 156255,14$ 1

$\Rightarrow$ Total cost of 5 s/c : $1 + 2 + 3 + 4 + 5 = 10,4 \cdot 10^5$

$\Rightarrow 208,7 \cdot 10^3$ \$ per s/c

SMAD pg 801
+
SMAD pg 665

14.3 Ground Segment & Operations Cost

via tabel 16-13 pg 665

	KIPS
comm. & processing	7
tel "	3
	9
	12
	15
	12
	5
	4
	20
	5
	5
	3
	100

$K = 2^{10} = 1024 \Rightarrow 100\,K = 100 \cdot 1024 \times 16$ bits

$= 1638400$ bits

$\div 8 \rightarrow$ byte

$\div 1024 \rightarrow$ kB

$\div 1024 \rightarrow$ MB

PPP

$= 0{,}20$ MByte

ADA

14.4 Average Unit Cost

geg: 15 a/c busses → total cost 750 M\$ and gone to make a total of 25 at a total cost of 1125 M \$. company expects to sell in total 50 busses over total life programme.

gvr: what will be the total and avg. single unit cost of the 50 bu's

opl: 15 a/c produced : avg unit cost (UC) $= \dfrac{750\text{ M\$}}{15} = 50\text{ M\$}$

25 a/c produced : $UC = \dfrac{1125\text{ M\$}}{25} = 45\text{ M\$}$

Hence with increasing numbers produced, UC decreases as expected from the learning effect.

Total cost and UC follow from:

$$UC = \frac{TC}{N} = TFU \times \frac{L}{N} = TFU \times \frac{N^B}{N} = TFU \times N^{B-1}$$

$$UC = TFU \times N^{\left(\frac{\ln(S/100\%)}{\ln 2}\right)} = TFU \times N^{\left(\frac{\ln x}{\ln 2}\right)} = TFU \times N^{-b}$$

Using the given data, we find expressions for UC with 2 unknowns (TFU & b):

(1) $50\text{ M\$} = TFU \times 15^{-b}$ ∧ (2) $45\text{ M\$} = TFU \times 25^{-b}$

$\Rightarrow \frac{(1)}{(2)} : \frac{50}{45} = 1 \cdot \left(\frac{15}{25}\right)^{-b}$

??? Hoe ?? $\Rightarrow b = 0{,}206$

$\Rightarrow TFU = \dfrac{50}{15^{-0{,}206}} = 87{,}3\text{ M\$}$

$\Rightarrow$ 50 busses: $U(50) = TFU \times 50^{-0{,}206} = 39\text{ M\$}$

$TC = 50 \times 39\text{ M\$} = 1950\text{ M\$}$

14.5 Cost Budgetting

!!? tabel 20-11 pg 801 ? of 799 ?!

Facilities	6 %	€ 6 M
Equipment	27 %	€ 27 M
Software	33 %	€ 33 M
Logistics	5 %	€ 5 M
Systems Level		
Management	6 %	€ 6 M
Systems Eng.	10 %	€ 10 M
Product Ass.	5 %	€ 5 M
Integr. & Test	8 %	€ 8 M
Totaal	100 %	100 M Euro

14.7 Cost Estimate from Component Cost

$$TC = 60\,M\$ + 40\,M\$ = 100\,M\$$$

The Standard Error (SE) follows from the SE of the bus and payload

$$SE = \sqrt{\sum_i SE_i} = \sqrt{\underbrace{24^2}_{0{,}4 \cdot 60 = 24} + \underbrace{8^2}_{0{,}2 \cdot 40 = 8}} = 25{,}3\,M\$$$

or $(SE)_{\%C} = 25{,}3\%$

__opm__: in practice the cost is higher than the sum of the costs of the components due to costs for integration and testing and for the management of the latter 2 activities

Hfdstuk 15 : MAIT ; B pg 259 - 279

MAIT : manufacturing, assembly, Integration and Test

15.1 pg 273-274

- prototype ⟺ protoflight development

* completely new designs * representative model with qualif. hardware => full qual. testprog. * one complete add. S/C * high cost	⟺	* qual. model is refurbished for flight * qual. test. prog. applied, only half the full test durations * TFU costs are 1/3 of cost of TFU in prototype approach, but life of S/C is 1,5 times mission life

- qualification ⟺ acceptance testing

=> are not yet qualified ⟺ were earlier qualified: verify that no workmanship errors have occurred.

- functional ⟺ environmental testing

pg 271 slide 1

15.2 (SSE pg 575)

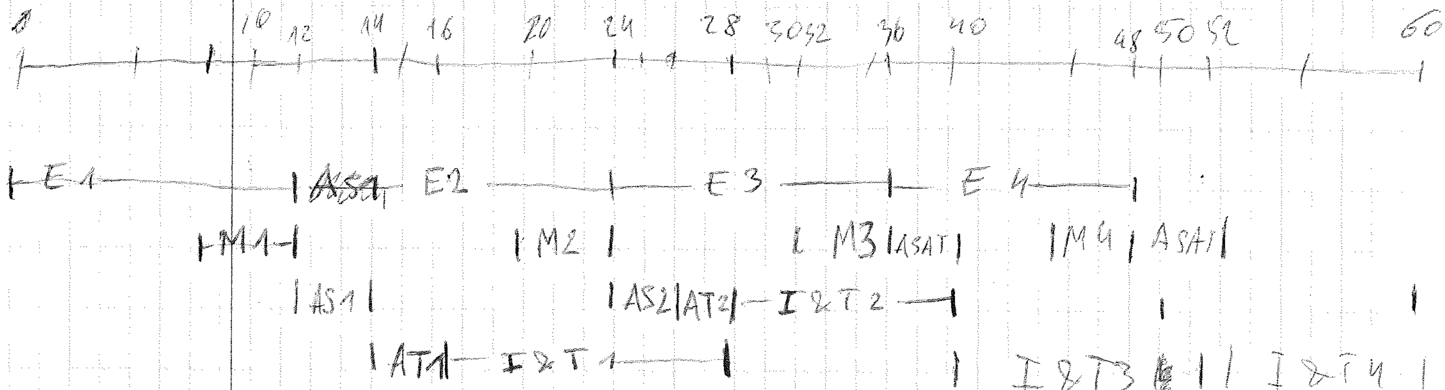
what is a verification matrix for?
It identifies how every design and mission requirement, as stated in the specifications, will be verified. (by analysis or test)
... see pg 575

15.3 Development Tests

- static tests
- dynamic tests
- thermal tests
- electric system tests
- solar panel tests

15.4 MAIT Scheduling

Mech part & mat : 4 months
Elect. : 12 months
assembly : 2 months
acceptance tests : 2 months



8 months
⇓
te weinig!

Dus: per lijn 3 s/c in 60 months

⇒ 7 lijnen met 6 lijnen die 3 s/c maken en 1 lijn die 2 s/c maken.
remaining 8 months ⇒ margin!