AE2111-II Spacecraft Report

Link budget and ADCS calculations

Group 51

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AE2111-II: Systems Design

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1

Link budget tool

1.1. Tool development process

The link budget tool was developed to aid the calculations in the satellite communication case studies. By having the computer calculate the link budget, manual calculations can be kept to a minimum, hence avoiding human error.
Starting off, the sample calculation of the link budget of the BIRD spacecraft was used from the recap lecture on telecommunications [1]. Most formulas used in the link budget calculator are copied from that presentation, and entered into the Python link budget calculation script as functions.
Most formulas given apply one-to-one to the case studies presented, while others, like the distance calculation need to be adaptive for both Earth orbit as well as interplanetary missions. For these cases, using Python over Excel proved to be the right choice, as differentiating between such cases can make an Excel sheet very messy.
Similarly the equation for the generated data rate had to be modified to suit the data which gave the pixel size in $arcminutes$ instead of m.

1.1.1. Assumptions

When collecting equations and data for the link budget calculator, it became clear that not every value is always given, and that simplifications are needed to make the calculator universal.

1. In the peculiar case of a Moon orbiter the formula for calculating interplanetary distances does not apply, so instead we just used an average Moon-Earth distance of $384.4 \times 10^6\ m$. This is good enough because the orbital altitude of the orbiter around the Moon is very small compared to this distance.
2. It was assumed that the data would be transmitted uncompressed. This eases calculations and reduces the complexity of the on-board computer. The coding used is either 8FSK or BPSK Viterbi and the corresponding required SNR is read from the graph in [2] and then entered as a discrete option in the script.
3. A worst case attenuation loss of $-0.5\ dB$ was assumed for all cases, as this seems to be a reasonable worst case estimate accounting for weather, elevation and atmospheric attenuation. It was used in the sample calculation as well, which
4. It was unclear which of the given transmitter and receiver loss factors belonged to the spacecraft and the ground station in down- or uplink. In the end this does not matter because they both get multiplied in the link budget, so their order is of no influence.
5. A system noise temperature of $135\ K$ was assumed. This value was taken from the lecture with the sample calculations on the BIRD spacecraft, as finding data on the system noise temperature of each individual satellite proved rarely possible.

6. Likewise, the receiving antenna pointing offset angle was taken to be 10% of the half-power angle of the receiving antenna, as this also seemed realistic and was used in the sample calculation on the BIRD S/C.

1.2. User manual

To use the tool, you can download a copy from GitHub. You will need at least the *linkdata.xlsx*, *original_linkdata.xlsx*, *spaceFormulae.py* and *spacecraft.py* for the link budget tool alone. Put all files in the same folder, then run the Python file *spacecraft.py*. This will print the down- and uplink budget and its components for each satellite. When you want to modify some parameters because the budget does not close, or because you could save weight by lowering the margin (if it is greater than 3 dB for instance), you can do so in the *linkdata.xlsx* spreadsheet. There the values in the white cells can be adjusted within reasonable limits, but the red cells cannot be changed. After saving the spreadsheet, run the Python script again to see by how much the link budget improved! If you want to compare the modified link budget with the original starting point, you can run the Python script with the argument *-o* or *–original*, then it will calculate the link budget using the data from *original_linkdata.xlsx*.

1.2.1. Capabilities

This tool can calculate the link budget margin when given a filled spreadsheet with values presented like in *linkdata.xlsx*.
One of the limitations is that the encoding for now is fixed to FSK8, because that was the initial coding, and the required SNR for that is hard-coded into the script as 10. This could be resolved by either fitting curves for each coding presented in the graph from [2], or by looking up existing formulas for the required SNR given a BER. This latter option has been tried, but as the results from the formula obtained from [3] don't line up with the graph from the lectures, it was decided to stick with an FSK8 coding. In case needed this can be added in the future when a link budget requires a greater coding gain for it to be able to close.

Because of the assumptions made in subsection 1.1.1 and because the link budget tool was mostly tailored to the given data set, the tool is limited to calculations of similar missions with the data being given in the same format[1]. For other uses it would need to be generalised to accept different types of sensors (not only line scanners) and would ideally use as few assumptions as possible as these limit the tool's scope.

1.3. Tool interface

The interface of the link budget tool is an Excel spreadsheet, where the values from the table given in [4] can be tweaked. After saving the spreadsheet, running the Python script will print the link budget and its components for the down- and uplink of each satellite case study, as seen in Figure 1.1.

[1]To give an example, this includes a pixel resolution given in $arcminutes$ instead of m, which implies a different pixel arrangements within the sensor: a circular pixel array has a constant angular resolution and a straight line of pixels has a constant ground resolution along the swath width

pictures/tool_interface.png

Figure 1.1: This is the interface of the link budget tool

2

Telecommunications

2.1. Earth observation 3U CubeSat

The original downlink and uplink margins were $-34.649\ dB$ and $12.84\ dB$ respectively. Therefore, only the downlink needs to be closed, after which we will tune down the uplink margin to about $\approx 3\ dB$ to save resources.

The first change involves increasing the transmitting power from $2\ W$ to $8\ W$. This is reasonable as the transmission window is very short $\left(\frac{0.5\ h}{24\ h}\right)$, so it should be ok to draw more than half of the produced power for a fraction of the orbit.
Next up is the S/C antenna diameter. Increasing this from $0.1\ m$ to $0.5\ m$ helps a lot, and is possible if we use a deployable parabolic antenna comparable to [5].
Changing the orbit altitude affects both velocity, hence scanned lines per second as well as the distance, affecting the space loss. These effects partially cancel each other out, so the margin only slowly becomes better as the orbital altitude increases. Because this CubeSat is supposed to fly in LEO to capture images with a high level of detail, we can't increase the orbit size too much. For that reason we choose the orbital altitude to increase from $350\ km$ to $700\ km$.
Next, the original pointing offset of this CubeSat, being 5°, is relatively large. With an ADCS that still should fit in a 3U CubeSat we can realistically achieve about 2° of pointing error judging from [6], by using reaction wheels.
Because this link budget gap was relatively large to start with, we've had to narrow down the swath width from 20° to 5°, as well as reduce the payload duty cycle from 100% to 40%. This reduction in duty cycle is doable, because for many polar Earth observation orbits you fly over the night side of Earth for half an orbit, so a visible light camera or line scanner will only be able to collect useful daytime information during one half of the orbit.
Finally, after changing the coding from 8FSK to BPSK Viterbi, the margin comes to be positive $0.468\ dB$, which is not a full $3\ dB$ margin, but in this case I would not want to diminish the payload performance any more, because 5° swath width already is not a lot. That is why the link budget of this option is printed in Table 2.2.
If the $3\ dB$ of margin are really required, the swath width could be reduced to 3.2° and the duty cycle could be reduced to 34%.

As the uplink budget already closes, I only lowered the transmitting power of the groundstation from $400\ W$ to $10\ W$, because then the SNR margin still is $12.591\ dB$, but the power consumption is lower. An added benefit is that a lower transmitting power gives less RF pollution, meaning that other links on Earth are disturbed less by our transmissions.

Parameter	Value $[dB]$	Unit
P	3.01	W
Ll	-0.969	$-$
Gt	4.653	$-$
La	-0.5	$-$
Gr	24.653	$-$
Ls	-165.901	$-$
Lpr	-0.153	$-$
Lr	-1.549	$-$
1/R	-95.19	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	-24.649	$-$
Eb/N0 required	10.0	$-$
SNR margin	-34.649	$-$

Table 2.1: Original downlink budget Earth 3U CubeSat

Parameter	Value $[dB]$	Unit
P	9.031	W
Ll	-0.969	$-$
Gt	18.632	$-$
La	-0.5	$-$
Gr	24.653	$-$
Ls	-169.026	$-$
Lpr	-0.252	$-$
Lr	-1.549	$-$
1/R	-81.849	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	5.468	$-$
Eb/N0 required	5.0	$-$
SNR margin	0.468	$-$

Table 2.2: Closed downlink budget Earth 3U CubeSat

Parameter	Value $[dB]$	Unit
P	26.021	W
Ll	-0.969	$-$
Gt	23.936	$-$
La	-0.5	$-$
Gr	3.936	$-$
Ls	-165.185	$-$
Lpr	-0.148	$-$
Lr	-1.549	$-$
1/R	-70.0	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	22.84	$-$
Eb/N0 required	10.0	$-$
SNR margin	12.84	$-$

Table 2.3: Original uplink budget Earth 3U CubeSat

Parameter	Value $[dB]$	Unit
P	10.0	W
Ll	-0.969	$-$
Gt	23.936	$-$
La	-0.5	$-$
Gr	17.916	$-$
Ls	-168.309	$-$
Lpr	-0.232	$-$
Lr	-1.549	$-$
1/R	-70.0	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	17.591	$-$
Eb/N0 required	5.0	$-$
SNR margin	12.591	$-$

Table 2.4: Closed uplink budget Earth 3U CubeSat

2.2. Lunar explorer 12U CubeSat

Initially, the downlink budget margin for the Lunar orbiter is -24.229 dB, whereas the margin of the uplink budget comes in at positive 1.295 dB. This again means that we will first close the downlink budget. By then the uplink will also benefit from the improvements already made, so we can reduce the margin a bit to save resources.

Starting with the transmitter power, the Moon CubeSat is originally using 8 W out of a total of 40 W for transmission purposes. This can be increased, but not as drastically as was done for the Earth CubeSat. This is because this satellite has a higher transmission ratio, so we will be transmitting at higher power while at the same time operating the payload. Hence we only increase the transmitting power to 28 W. It was chosen to transmit for each half of the orbit when Earth is visible, to maximise the time of contact (so the payload downlink time is increased to 12 h). This means that we need a network of antennas on Earth, but that already exists and can time can be rented (for example at stations like Redu Station [7]).
Next, the downlink frequency is changed from 2.2 GHz to 8.4 GHz. This is the same frequency as the interplanetary satellites in this tutorial are using, and it does help a lot in closing the link budget.

Furthermore the pointing offset it reduced to 0.5°, for the same reasons as with section 2.1. In this case, though, a smaller number of 0.5° was chosen as the satellite is a 12U CubeSat, so it has a higher mass moment of inertia and as such can be pointed more precisely because disturbance torques have a smaller effect.
The duty cycle of the payload had to be reduced to 30% to make the downlink budget close in conjunction with using the BPSK Viterbi coding from [1] instead of the original 8FSK coding. This manages to bring the SNR margin up to 3.047 dB, thereby satisfying the requirement of having at least 3 dB

For the uplink budget we can reduce the transmitter power from 400 W to 100 W while still getting a margin of 11.885 dB. This margin satisfies the requirement of being at least 3 dB and is similar to the margin for the Earth CubeSat.

Parameter	Value $[dB]$	Unit
P	9.031	W
Ll	-0.969	$-$
Gt	14.195	$-$
La	-0.5	$-$
Gr	38.632	$-$
Ls	-210.986	$-$
Lpr	-0.132	$-$
Lr	-1.549	$-$
1/R	-69.249	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	-14.229	$-$
Eb/N0 required	10.0	$-$
SNR margin	-24.229	$-$

Table 2.5: Original downlink budget Moon 12U CubeSat

Parameter	Value $[dB]$	Unit
P	14.472	W
Ll	-0.969	$-$
Gt	25.832	$-$
La	-0.5	$-$
Gr	50.269	$-$
Ls	-222.623	$-$
Lpr	-0.163	$-$
Lr	-1.549	$-$
1/R	-64.02	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	8.047	$-$
Eb/N0 required	5.0	$-$
SNR margin	3.047	$-$

Table 2.6: Closed downlink budget Moon 12U CubeSat

Parameter	Value $[dB]$	Unit
P	26.021	W
Ll	-0.969	$-$
Gt	37.916	$-$
La	-0.5	$-$
Gr	13.479	$-$
Ls	-210.27	$-$
Lpr	-0.13	$-$
Lr	-1.549	$-$
1/R	-60.0	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	11.295	$-$
Eb/N0 required	10.0	$-$
SNR margin	1.295	$-$

Table 2.7: Original uplink budget Moon 12U CubeSat

Parameter	Value $[dB]$	Unit
P	20.0	W
Ll	-0.969	$-$
Gt	49.553	$-$
La	-0.5	$-$
Gr	25.116	$-$
Ls	-221.907	$-$
Lpr	-0.157	$-$
Lr	-1.549	$-$
1/R	-60.0	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	16.885	$-$
Eb/N0 required	5.0	$-$
SNR margin	11.885	$-$

Table 2.8: Closed uplink budget Moon 12U CubeSat

2.3. Mars orbiter 6U CubeSat

To begin with, the Mars orbiting 6U CubeSat has a down- and uplink margin of -57.826 dB and -18.108 dB respectively. This is a relatively large gap, but in this section we will attempt to solve this, by modifying the input parameters of its link budget.

Again, the transmitter power will be increased from 5 W to 15 W out of a total of 20 W, to not interfere with other subsystems like payload, ADCS and CD&H. Furthermore the diameter of the ground station antenna is increased from 10 m to 50 m. This corresponds to a large ground station, but as this is a mission to Mars, this expense is justifyable.
Next, the orbit altitude is increased from 500 km to 8000 km, in order to reduce orbital velocity, and hence the number of lines per second scanned. The pointing offset is left at 0.5°, similar to the Moon mission in section 2.2.
To bridge the still pretty big gap of -18.595 dB in the downlink margin, we need to increase the pixel size from 0.2 $arcmin$ to 1 $arcmin$, together with changing the coding from 8FSK to BPSK Viterbi. By doing this, a SNR margin of 0.385 dB is achieved. Similarly to section 2.1 this does not satisfy the 3 dB margin requirement, but as the payload capability already had to be limited by a lot, this becomes a trade-off. I chose to print the former, more capable, option in Table 2.10.
To meet the requirement the payload pixel size would need to be increased even further, namely to 1.4 $arcminutes$. This would then give an SNR margin of 3.307 dB, at the cost of even lower resolution scans.

The uplink margin after all these measures is 1.915 dB, so to close it we can increase the transmission power from 400 W to 600 W, giving it an uplink SNR margin of 3.676 dB.

Parameter	Value $[dB]$	Unit
P	6.99	W
Ll	-0.969	–
Gt	36.29	–
La	-0.5	–
Gr	56.29	–
Ls	-278.077	–
Lpr	-2.04	–
Lr	-1.549	–
1/R	-71.558	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	-47.826	–
Eb/N0 required	10.0	–
SNR margin	-57.826	–

Table 2.9: Original downlink budget Mars 6U CubeSat

Parameter	Value $[dB]$	Unit
P	11.761	W
Ll	-0.969	–
Gt	36.29	–
La	-0.5	–
Gr	70.269	–
Ls	-278.077	–
Lpr	-0.6	–
Lr	-1.549	–
1/R	-38.538	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	5.385	–
Eb/N0 required	5.0	–
SNR margin	0.385	–

Table 2.10: Closed downlink budget Mars 6U CubeSat

Parameter	Value $[dB]$	Unit
P	26.021	W
Ll	-0.969	–
Gt	54.89	–
La	-0.5	–
Gr	34.89	–
Ls	-276.677	–
Lpr	-1.511	–
Lr	-1.549	–
1/R	-50.0	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	-8.108	–
Eb/N0 required	10.0	–
SNR margin	-18.108	–

Table 2.11: Original uplink budget Mars 6U CubeSat

Parameter	Value $[dB]$	Unit
P	27.782	W
Ll	-0.969	–
Gt	68.869	–
La	-0.5	–
Gr	34.89	–
Ls	-276.677	–
Lpr	-0.468	–
Lr	-1.549	–
1/R	-50.0	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	8.676	–
Eb/N0 required	5.0	–
SNR margin	3.676	–

Table 2.12: Closed uplink budget Mars 6U CubeSat

2.4. Venus Explorer

The uplink margin of the mission was satisfied from the very beginning. Analysis of the downlink budget for the Venus mission has shown that the current downlink margin is $-25.193\ dB$.

Firstly, the spacecraft will be transmitting 100% Of the time. This means that we cannot consume too much power, because else there is none left for other systems like the payload. With this in mind, the transmission power is increased from 350 W to 800 W. Additionally, the ground station antenna is upgraded to a 70 m Deep Space Network [8] antenna, also because we need 24/7 connectivity with the spacecraft.
The pointing offset is already very good at 0.05°, so we only change the payload swath width angle from 45° to 10°, and reduce the payload duty cycle from 50% to 25%. Reducing the payload performance this far is not nice, but unavoidable, as otherwise no transmission would be possible. Lastly the coding is changed from the original 8FSK to the more efficient BPSK Viterbi coding.
All this together still does not quite manage to close the link budget, so new, expensive ground station receiving hardware is bought, with extra low noise levels. This brings the antenna – receiver loss factor from 0.7 to 0.9. With these modifications, a SNR margin of 0.303 dB is achieved, and this link budget is shown in Table 2.14. By reducing the duty cycle even further down to 13%, the required SNR margin is also met with 3.143 dB.

By the end of this optimisation, the uplink budget has further increased to 30.86 dB, so to save resources, the transmitting power of the ground station is reduced from 1000 W to 100 W. This brings the SNR margin down to 20.86 dB, which is still much greater than the required margin of 3 dB, so the uplink budget closes as well.

Parameter	Value $[dB]$	Unit
P	25.441	W
Ll	-0.458	–
Gt	39.914	–
La	-0.5	–
Gr	67.022	–
Ls	-271.704	–
Lpr	-0.131	–
Lr	-1.549	–
1/R	-80.527	$(bit/s)^-1$
1/k	228.601	$(J/K)^-1$
1/Ts	-21.303	K^-1
Eb/N0	-15.193	–
Eb/N0 required	10.0	–
SNR margin	-25.193	–

Table 2.13: Original downlink budget Venus Explorer

Parameter	Value $[dB]$	Unit
P	29.031	W
Ll	-0.458	–
Gt	39.914	–
La	-0.5	–
Gr	73.295	–
Ls	-271.704	–
Lpr	-0.131	–
Lr	-0.458	–
1/R	-70.985	$(bit/s)^-1$
1/k	228.601	$(J/K)^-1$
1/Ts	-21.303	K^-1
Eb/N0	5.303	–
Eb/N0 required	5.0	–
SNR margin	0.303	–

Table 2.14: Closed downlink budget Venus Explorer

Parameter	Value $[dB]$	Unit
P	30.0	W
Ll	-0.458	$-$
Gt	65.622	$-$
La	-0.5	$-$
Gr	38.514	$-$
Ls	-270.304	$-$
Lpr	-0.128	$-$
Lr	-1.549	$-$
1/R	-40.0	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	28.496	$-$
Eb/N0 required	10.0	$-$
SNR margin	18.496	$-$

Table 2.15: Original uplink budget Venus Explorer

Parameter	Value $[dB]$	Unit
P	20.0	W
Ll	-0.458	$-$
Gt	71.895	$-$
La	-0.5	$-$
Gr	38.514	$-$
Ls	-270.304	$-$
Lpr	-0.128	$-$
Lr	-0.458	$-$
1/R	-40.0	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	25.86	$-$
Eb/N0 required	5.0	$-$
SNR margin	20.86	$-$

Table 2.16: Closed uplink budget Venus Explorer

2.5. Europa imaging mission

Similar to the Venus mission the uplink budget of the mission was satisfied from the very start at a margin of about 23.5 dB and only needs adjustments to satisfy the downlink. This can be done by adjusting certain parameters of the satellite until the link budget is satisfied.

Firstly, taking into account that the maximum amount of power that is produced by the spacecraft is 800 W and an amount of this power has to be used to for function besides transmission. Therefor an increase from 150W to 600 W was deemed an appropriate amount. The loss factor in both transmitter and receiver power was not changed as both changed to be sufficient. To improve the downlink further the size of the antenna has to be increased. To keep it a realistic value it was increased to 3.7 m, the same size as the antenna of the Voyager satellites. The adjusting the pointing offset angle resulted in a minimal change to the link budget and is already at a high pointing accuracy. The biggest compromise is made in payload performance, where it is beneficial to the link budget to transmit as few pixels as possible. To achieve this, the pixel size would have to increase and swath width angle would have to be decreased. To have a realistic decrease the FOV of the New Horizons spacecraft was used as a minimum and therefor an angle of 0.4° was used. Then the pixel size was increased until the link budget was satisfied which resulted at a value 0.05 $arcminutes$. With the significant decrease in swath width angle and a change of coding from 8FSK to BPSK Viterbi, there is now a margin of 0.737 dB above the required margin of 3 dB.

With these downlink budget improvements, the uplink budget margin increased to 30.302 dB. This may be reduced by saving power, reducing the transmitting power from 1000 W to 100 W. This gives a final uplink budget margin of 20.302 dB.

Parameter	Value $[dB]$	Unit
P	21.761	W
Ll	-0.458	–
Gt	45.832	–
La	-0.5	–
Gr	73.192	–
Ls	-288.768	–
Lpr	-0.163	–
Lr	-1.549	–
1/R	-90.219	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	-33.574	–
Eb/N0 required	10.0	–
SNR margin	-43.574	–

Table 2.17: Original downlink budget Europa imager

Parameter	Value $[dB]$	Unit
P	27.782	W
Ll	-0.458	–
Gt	47.654	–
La	-0.5	–
Gr	73.192	–
Ls	-288.768	–
Lpr	-0.186	–
Lr	-1.549	–
1/R	-55.728	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	8.737	–
Eb/N0 required	5.0	–
SNR margin	3.737	–

Table 2.18: Closed downlink budget Europa imager

Parameter	Value $[dB]$	Unit
P	30.0	W
Ll	-0.458	–
Gt	71.792	–
La	-0.5	–
Gr	44.432	–
Ls	-287.368	–
Lpr	-0.151	–
Lr	-1.549	–
1/R	-30.0	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	33.496	–
Eb/N0 required	10.0	–
SNR margin	23.496	–

Table 2.19: Original uplink budget Europa imager

Parameter	Value $[dB]$	Unit
P	20.0	W
Ll	-0.458	–
Gt	71.792	–
La	-0.5	–
Gr	46.254	–
Ls	-287.368	–
Lpr	-0.168	–
Lr	-1.549	–
1/R	-30.0	$(bit/s)^{-}1$
1/k	228.601	$(J/K)^{-}1$
1/Ts	-21.303	$K^{-}1$
Eb/N0	25.302	–
Eb/N0 required	5.0	–
SNR margin	20.302	–

Table 2.20: Closed uplink budget Europa imager

3

ADCS

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3.1. ADCS: Earth 3U CubeSat

3.1.1. Sensors

For this satellite, a minimum pointing knowledge is 3600 arcsec. = 1 deg. Considering this, and a low earth orbit, a set of a magnetometer with a static earth sensor is sufficient, providing a set of two vectors, which is enough for 3-axis pointing knowledge. This set in total takes 0.65W of power and has a mass of 0.7kg. This simple, lightweight set of sensors goes well with the low required pointing knowledge accuracy. For redundancy, 2 such sets will be used.

3.1.2. Actuators

Assumptions: the firing time of thrusters is 2 s (example with BIRD S/C); a circular orbit at a constant altitude of 300 km above a spherical approximation of Earth; the reaction wheels are made of aluminium (e.g. RSI 45[9]) with a density of $\rho_{al.} = 2669\frac{kg}{m^3}$; maximum rotational speed of $\omega_{max} = 2000rpm = 209\frac{rad}{sec}$ (same source); margin factor, MF = 1.

Only thrusters

$$slew : 2{\cdot}F_T = \frac{I \cdot \omega}{L \cdot t}, \omega = \frac{\theta}{t} = \frac{\pi/6}{5} = 0.1047\frac{rad}{s}; 2{\cdot}F_T = \frac{0.01 \cdot 0.1047}{0.05 \cdot 5} = 0.0042N, F_T = 0.0021N. \quad (3.1)$$

$$disturbance : \; 2{\cdot}F_T = \frac{T_D \cdot (1 \; + \; MF)}{L}, \frac{10^-6 \cdot (1+1)}{2 \cdot 0.05} \; = 0.00002N, each \; of \; the \; two \; thrusters \quad (3.2)$$

The second result is smaller than the first, which makes the slew manoeuvre the driving requirement; since the required thrust os between 1 mN and 1 N, the cold gas thrusters are appropriate.

Reaction Wheels and thrusters for momentum dumping

$$slew : \; T \; = \; \frac{4 \cdot I \cdot \theta}{t^2} = \frac{4 \cdot 0.01 \cdot \pi/6}{5^2} = 0.000838Nm \quad (3.3)$$

$$orbital \; period : \; P = \sqrt{\frac{4 \cdot \pi^2 \cdot r^3}{G \cdot M_{Venus}}} = \sqrt{\frac{4 \cdot \pi^2 \cdot (6671000)^3}{6.6743015 \cdot 10^{-11} \cdot 5.97 \cdot 10^{24}}} = 5423 \; seconds \quad (3.4)$$

$$momentum \; stored \; due \; to \; counteraction : \; h = \frac{\sqrt{2} \cdot T_D \cdot P}{8} = \frac{\sqrt{2} \cdot 10^-6 \cdot 5423}{8} = 0.00096Nms \quad (3.5)$$

$$the \; thrust \; for \; momentum \; dumping : 2 \cdot T_T = \frac{h}{t \cdot L} = \frac{0.00096}{2 \cdot 0.05} = 0.0096N, \; 0.0048N \; each. \quad (3.6)$$

Finally, calculating the wheel sizes:

$$h = \omega \cdot I = \omega \cdot 0.5 \cdot \rho \cdot \pi \cdot h_{RW} \cdot r_{RW}^4 \quad (3.7)$$

$$r_{RW} = \left(\frac{h}{\omega_{max} \cdot 0.5 \cdot \rho \cdot \pi \cdot h_{RW}}\right)^{\frac{1}{4}} = \left(\frac{0.00096}{209 \cdot 0.5 \cdot 2669 \cdot \pi \cdot 0.005}\right)^{\frac{1}{4}} = 0.0216m \quad (3.8)$$

The wheel thickness was found by trial and error, so that the radius of the wheel is larger than its thickness, but small enough that it fits in the satellite, so smaller than 0.1 m. Wheel diameter: 43.2 mm. In this case it is clear that the thrusters only option is preferable, since with the reaction wheels the thrusters have to be larger than without.

3.2. ADCS: Lunar explorer 12U CubeSat

3.2.1. Sensors

For the Lunar explorer, one star sensor and two Sun sensors were chosen as attitude sensors. Although one star sensors gives sufficient measurement, sun sensors are added to prevent single point of failure. Since these sensor are capable of work under the slew rate of 1.5°/sec, gyroscope is not added. Also, they satisfy required pointing accuracy of 1800 arcsec [10][11]. Magnetometer cannot be used because moon's magnetic field is very weak compared to the earth and an earth sensor is also not suitable for non-Earth orbit.

3.2.2. Actuators

Assumptions:

- Firing time of thrusters: 2 s (example with BIRD S/C).
- The satellite is in a circular orbit
- The material of the wheels is aluminium (e.g. RSI 45 [9]): $\rho_{al.} = 2669\frac{kg}{m^3}$
- Maximum rotational speed of the wheel: $\omega_{max} = 2000rpm = 209\frac{rad}{sec}$ [9]

Choice 1: Only thrusters

- slew: the required angular velocity is $\pi/2\ rad$ in 60 seconds

$$2 \cdot F_T = \frac{I \cdot \omega}{L \cdot t} = \frac{10^{-1} \cdot \frac{\pi/2}{60}}{0.1 \cdot 60} = 4.37 \cdot 10^{-3} N \rightarrow F_T = 2.18 \cdot 10^{-3} N \tag{3.9}$$

- disturbance: marginal factor is assumed to be 2

$$2 \cdot T_F = \frac{T_D \cdot (1\ +\ MF)}{L} = \frac{10^{-8}(1+2)}{0.1} = 3 \times 10^{-7} N \rightarrow T_F = 1.5 \cdot 10^{-8} N \tag{3.10}$$

The required thrust for slew is bigger than the latter, so $F_T = 2.18 \cdot 10^{-3}\ N$ is the driving requirement.

Choice 2: a pair of thrusters and a reaction wheel

$$\text{Torque to slew}: \ T = \frac{4 \cdot I \cdot \theta}{t^2} = \frac{4 \cdot 10^{-1} \cdot \pi/2}{60^2} = 1.745 \cdot 10^{-4} N \tag{3.11}$$

$$\text{Orbital period}: \ P = \sqrt{\frac{4 \cdot \pi^2 \cdot r^3}{G \cdot M_{Moon}}} = \sqrt{\frac{4 \cdot \pi^2 \cdot (1730000 + 1000000)^3}{6.674 \cdot 10^{-11} \cdot 7.342 \cdot 10^{22}}} = 12853\ seconds \tag{3.12}$$

$$\text{Thus, disturbance per orbit is}: \ h = \frac{\sqrt{2}}{2} \cdot T_D \cdot \frac{P}{4} = \frac{\sqrt{2} \cdot 1.745 \cdot 10^{-4} \cdot 12853}{8} = 0.396\ Nms \tag{3.13}$$

$$\text{Required force for thruster}: \ 2 \cdot T_t = \frac{h}{t \cdot L} = \frac{0.396}{2 \cdot 0.1} = 1.98N \Rightarrow T_t = 0.99N \tag{3.14}$$

Momentum wheel sizing: The height of the wheel and maximum rotational rate was decided by iteration as 20mm.

$$h = \omega \cdot I = \omega \cdot 0.5 \cdot \rho \cdot \pi \cdot h_{RW} \cdot r_{RW}^4$$

$$\rightarrow r_{RW} = \left(\frac{h}{\omega_{max} \cdot 0.5 \cdot \rho \cdot \pi \cdot h_{RW}}\right)^{\frac{1}{4}} = \left(\frac{0.3964}{209 \cdot 0.5 \cdot 2669 \cdot \pi \cdot 0.02}\right)^{\frac{1}{4}} = 0.0689m = 68.9mm \tag{3.15}$$

Wheel diameter: 138 mm. Considering the result, it is obvious that thruster only option is preferable because the thruster does not need to produce bigger force. A pair of electric thrusters is appropriate in this case.

3.3. ADCS: Mars 6U CubeSat

3.3.1. Sensors

Requirement for the pointing knowledge: 1800 arcsec. The only combination that provides enough redundancy while using only two omponents is the combination with two star trackers, which would satisfy the requirements [12].

3.3.2. Actuators

Assumptions: firing time of thrusters: 2 s (example with BIRD S/C); the satellite is in a circular orbit at 500 km; the material of the wheels is aluminium (e.g. RSI 45, Collins Aerospace): $\rho_{al.} = 2669\frac{kg}{m^3}$; maximum rotational speed of the wheel: $\omega_{max} = 2000rpm = 209\frac{rad}{sec}$ (same source); height of the wheel is 10 mm (plausible value achieved by iteration)

Only thrusters

$$slew:\ 2 \cdot F_T = \frac{I \cdot \omega}{L \cdot t},\ angular\ velocity\ required:\ \omega = \frac{\theta}{t} = \frac{10 \cdot \pi}{180 \cdot 30} = 5.8 \cdot 10^{-3} rad/s \tag{3.16}$$

$$2 \cdot F_T = \frac{5 \cdot 10^{-2} \cdot 5.8 \cdot 10^{-3}}{0.1 \cdot 30} = 9.7 \cdot 10^{-5} N = 0.097mN.\ \ F_T = 0.049mN each \tag{3.17}$$

$$disturbance:\ 2 \cdot F_T = \frac{T_D \cdot (1\ +\ MF)}{L},\ assuming\ margin\ factor\ to\ be\ 2\ (there\ are\ two\ thrusters): \tag{3.18}$$

$$\frac{10^{-5} \cdot (1+2)}{0.1}\ =\ 3 \cdot 10^{-4} N,\ \ 1.5 \cdot 10^{-4} N = 0.15mN\ each\ of\ the\ two\ thrusters. \tag{3.19}$$

The second result is smaller than the first, which makes the slew manoeuvre the driving requirement. Since the largest required thrust is smaller than 10 mN, electric thrusters are appropriate.

Reaction Wheels and thrusters for momentum dumping

Sizing the wheels for the slew manoeuvre and counteracting disturbance torques:

$$T\ =\ \frac{4 \cdot I \cdot \theta}{t^2} = \frac{4 \cdot 5 \cdot 10^{-2} \cdot 10 \cdot \pi/180}{30^2} = 3.88 \cdot 10^{-5} Nm \tag{3.20}$$

$$momentum\ stored\ due\ to\ counteraction:\ h = \frac{\sqrt{2} \cdot T_D \cdot P}{8}, \tag{3.21}$$

In order to calculate the disturbance per orbit it is necessary to know the orbital period:

$$P = \sqrt{\frac{4 \cdot \pi^2 \cdot r^3}{G \cdot M_{Mars}}} = \sqrt{\frac{4 \cdot \pi^2 \cdot (3389500 + 500000)^3}{6.6743015 \cdot 10^{-11} \cdot 6.4171 \cdot 10^{23}}} = 7365\ seconds \tag{3.22}$$

$$h = \frac{\sqrt{2} \cdot T_D \cdot P}{8} = \frac{\sqrt{2} \cdot 10^{-5} \cdot 7365}{8} = 0.013\ Nms \tag{3.23}$$

$$the\ thrust\ for\ momentum\ dumping: 2 \cdot T_T = \frac{h}{t \cdot L} = \frac{0.013}{2 \cdot 0.1} = 0.065N,\ 0.0325N\ each. \tag{3.24}$$

Hence, the cold gas thrusters (between 1mN and 1N) are appropriate. Finally, calculating the wheel sizes:

$$h = \omega \cdot I = \omega \cdot 0.5 \cdot \rho \cdot \pi \cdot h_{RW} \cdot r_{RW}^4 \tag{3.25}$$

$$r_{RW} = \left(\frac{h}{\omega_{max} \cdot 0.5 \cdot \rho \cdot \pi \cdot h_{RW}}\right)^{\frac{1}{4}} = \left(\frac{0.013}{209 \cdot 0.5 \cdot 2669 \cdot \pi \cdot 0.01}\right)^{\frac{1}{4}} = 35mm \tag{3.26}$$

Wheel diameter: 70 mm. In this case it is clear that the thrusters only option is preferable, since with the reaction wheels the thrusters have to be larger than without.

3.4. ADCS: Venus mission

3.4.1. Sensors

In order to obtain the position of the spacecraft two star trackers were chosen. Both of them provide accuracy of 5 arcsecond on two axes and 30 arcsecond on the third, which satisfies the required pointing knowledge of 50 arcsecond [12]. Each of the star trackers is able to provide information about all three axes, so the system is redundant.

3.4.2. Actuators

Assumptions: firing time of thrusters: 2 s (example with BIRD S/C);the satellite is in a circular orbit at 800 km; the material of the wheels is aluminium (e.g. RSI 45[9]): $\rho_{al.} = 2669\frac{kg}{m^3}$; maximum rotational speed of the wheel: $\omega_{max} = 2000rpm = 209\frac{rad}{sec}$ [9]; height of the wheel is 10 mm (plausible value achieved by iteration), since there are two thrusters, margin factor for thrusters-only configuration is 2.

Only thrusters

$$slew:\ 2 \cdot F_T = \frac{I \cdot \omega}{L \cdot t},\ angular\ velocity\ required:\ \omega = \frac{\theta}{t} = \frac{\pi}{10} = 0.3141 rad/s \tag{3.27}$$

$$2 \cdot F_T = \frac{400 \cdot 0.3141}{0.75 \cdot 10} = 16.8N,\ \ F_T = 8.4N. \tag{3.28}$$

$$disturbance:\ 2{\cdot}F_T = \frac{T_D \cdot (1\ +\ MF)}{L} = \frac{0.0005 \cdot (1+2)}{0.75}\ =\ 2{\cdot}10^{-3}N,\ \ 1{\cdot}10^{-3}N\ each\ of\ the\ two\ thrusters. \tag{3.29}$$

The second result is smaller than the first, which makes the slew manoeuvre the driving requirement. Since the largest required thrust is larger than 1 N, mono-propellant type of thruster will be used.

Reaction Wheels and thrusters for momentum dumping

Sizing the wheels for the slew manoeuvre and counteracting disturbance torques:

$$T\ =\ \frac{4 \cdot I \cdot \theta}{t^2} = \frac{4 \cdot 400 \cdot \pi}{10^2} = 50.3Nm \tag{3.30}$$

In order to calculate the disturbance per orbit it is necessary to know the orbital period:

$$P = \sqrt{\frac{4 \cdot \pi^2 \cdot r^3}{G \cdot M_{Venus}}} = \sqrt{\frac{4 \cdot \pi^2 \cdot (6052000 + 800000)^3}{6.6743015 \cdot 10^{-11} \cdot 4.8675 \cdot 10^{24}}} = 6252.4\ sec.; \tag{3.31}$$

$$momentum\ stored\ due\ to\ counteraction:\ h = \frac{\sqrt{2} \cdot T_D \cdot P}{8} = \frac{\sqrt{2} \cdot T_D \cdot P}{8} = \frac{\sqrt{2} \cdot 0.0005 \cdot 6252}{8} = 0.39\ Nms \tag{3.32}$$

$$the\ thrust\ for\ momentum\ dumping: 2 \cdot T_T = \frac{h}{t \cdot L} = \frac{0.39}{2 \cdot 0.75} = 0.26N,\ 0.13N\ each. \tag{3.33}$$

Hence, the cold gas thrusters (between 1mN and 1N) are appropriate. Finally, calculating the wheel sizes:

$$h = \omega \cdot I = \omega \cdot 0.5 \cdot \rho \cdot \pi \cdot h_{RW} \cdot r_{RW}^4 \tag{3.34}$$

$$r_{RW} = \left(\frac{h}{\omega_{max} \cdot 0.5 \cdot \rho \cdot \pi \cdot h_{RW}}\right)^{\frac{1}{4}} = \left(\frac{0.39}{209 \cdot 0.5 \cdot 2669 \cdot \pi \cdot 0.01}\right)^{\frac{1}{4}} = 81mm \tag{3.35}$$

Wheel diameter: 162 mm. The option with the reaction wheels and the cold gas thrusters is clearly preferable, since each wheel would weigh only one-fifth of a kilogram and provide for more precise control.

3.5. ADCS: Europa mission

3.5.1. Sensors

The Europa mission requires a high pointing accuracy with-in 50 $arcsec$ around all axes. Due to this a star sensors should be used do to their adherent accuracy. From the one sited it proves and accuracy of <1 arcsec in 2 axis and <10 in the final one. Although one star sensor would be sufficient as they provide for the task in order to not have a single point of failure a second one should be implemented for redundancy in case failure occurs on the first star sensor. Magnetometers, Sun Sensors and horizon sensors do not provide sufficient pointing knowledge.

3.5.2. Actuators

The 2 actuator configurations that are going to be explored one where only thrusters are used and one where both reaction wheel and thrusters are used for attitude control is used.
Assumptions made

- Firing time of 2 sec (example BIRD S/C)
- A perfectly circular orbit at 500 km [r_e] around Europa with influences from Saturn and it's moons assumed negligible.
- Assumed that Europa is a prefect sphere and that all of it's mass is concentrated at it's center.

Some details about Europa have to known where the radius of the moon is R_{eu} is 1,560.8 km , its mass is $4.7998 \cdot 10^{22}$ m gravitational constant $6.673 \cdot 10^{-11}$
Only Thrusters

$$Slewrate: \quad \frac{\theta}{t} = \omega = \frac{\pi}{60} = 0.0523 rad/s \quad F_T = \frac{I \cdot \omega}{L \cdot t \cdot 2} = \frac{1500 \cdot 0.0523}{1.5 \cdot 60} = 0.43N \tag{3.36}$$

$$Disturbances: \quad T_F = \frac{T_D \cdot (1 + MF)}{2 \cdot L} = \frac{10^{-1}(1+1)}{2 \cdot 1.5} = 6.7 \times 10^{-2} N \tag{3.37}$$

Therefor the slew rate is the driving requirement at 0.43 N
Thrusters + Reaction wheel

$$T = \frac{4 \cdot I \cdot \theta}{t^2} = \frac{4 \cdot 1500 \cdot \pi}{60^2} = 5.24N \tag{3.38}$$

$$T = \sqrt{\frac{4 \cdot \pi^2 \cdot (R_{Eu} + r_{Eu})^3}{G \cdot M_{Eu}}} = \sqrt{\frac{4 \cdot \pi^2 \cdot ((1560.8 + 500) \cdot 10^3)^3}{6.6743015 \cdot 10^{-11} \cdot 6.673 \cdot 10^{22}}} = 8808 \; seconds = 146 \; minutes] \tag{3.39}$$

To find the amount of disturbances there are per orbit.

$$h = \frac{\sqrt{2}}{2} \cdot T_D \cdot \frac{P}{4} = \frac{\sqrt{2}}{2} \cdot 5.24 \cdot \frac{8808}{4} = 8160 \; Nms \tag{3.40}$$

The needed thrust per thruster

$$T_t = \frac{h}{2 \cdot t \cdot L} = \frac{8160}{2 \cdot 2 \cdot 1.5} = 1360N \tag{3.41}$$

Estimating the size of the wheel

$$h = \omega \cdot I = \omega \cdot 0.5 \cdot \rho \cdot \pi \cdot h_{RW} \cdot r_{RW}^4$$

$$r_{RW} = \left(\frac{h}{\omega_{max} \cdot 0.5 \cdot \rho \cdot \pi \cdot h_{RW}} \right)^{\frac{1}{4}} = \left(\frac{8160}{209 \cdot 0.5 \cdot 2700 \cdot \pi \cdot 0.15} \right)^{\frac{1}{4}} = 0.498m = 498mm \tag{3.42}$$

Wheel diameter: 996 mm. Therefor for this case a pair of small thursters would be best as they do not have to provide a lot of force though out the orbit.

Bibliography

[1] A. Cervone. Spacecraft: Recap, practical examples and exercises, 2019. (Retrieved October 10, 2019).

[2] A. Cervone. Spacecraft telecommunications, 2019. (Retrieved October 12, 2019).

[3] Atlanta RF. Link budget analysis: Digital modulation, part 2, June 2013. URL https://www.atlantarf.com/FSK_Modulation.php.

[4] A. Cervone. Spacecraft tutorial assignment - september 2019, 2019. (Retrieved October 10, 2019).

[5] eoPortal. Raincube (radar in a cubesat) - a precipitation profiling mission, June 2019. URL https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/raincube-radar-in-a-cubesat-a-precipitation-profiling-mission.

[6] Christopher M. Pong. On-orbit performance & operation of the attitude & pointing control subsystems on asteria, 2018. URL https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4173&context=smallsat.

[7] ESA. Redu station, 2019. URL https://www.esa.int/Enabling_Support/Operations/Estrack/Redu_station.

[8] NASA. 70-meter antenna, 2019. URL https://deepspace.jpl.nasa.gov/about/complexes/70-meter/.

[9] Collins aerospace. URL https://www.rockwellcollins.com/Products-and-Services/Defense/Platforms/Space/RSI-45-Momentum-and-Reaction-Wheels.aspx. (Retrieved October 20, 2019).

[10] Nst-3 nano star tracker. URL https://www.cubesatshop.com/product/nst-3-nano-star-tracker/. (Retrieved October 20, 2019).

[11] Fine sun sensor, bradford. URL
http://bradford-space.com/products-aocs-fine-sun-sensors.php. (Retrieved October 20, 2019).

[12] Vectronic Aerospace GmbH. Star tracker vst-68m, 2019. URL
https://vectronic-aerospace.com/star-tracker-vst-68m/.