ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

EE-589 : Semester Project - Minor in Space Technologies

LUNAR CAMERA PROJECT

Mechanical design of the optical unit and structural subsystem for a lunar camera

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1. Introduction

The project was initiated by the Moon Village Association (MVA) (ref 17). It is a non-governmental association which regulates the exploration program of lunar missions. The MVA also works on the development of space technologies: the Payload1 project is a part of it.

The Payload 1 project is the first technical mission set by the MVA. Its goal is:

“To reenact the Overview Effect, a psychological effect that took place after the return of astronauts from Apollo 11 mission. At the sight of planet Earth from the moon, the person subject to this effect presents a feeling of awareness of the Humanity as a whole, and the fragile equilibrium of life on Earth. The reenactment of the Overview effect is used as a mean to foster international collaboration between public and private actors” (ref 16)

The eSpace, the Space Center of EPFL, was assigned the development of the Payload 1. In order to “reenact the Overview Effect”, the goal is to send a lunar lander equipped with a camera on the Moon’s surface. The camera will then take pictures of the Earth and send them (back to Earth). The launching, travelling and landing part of this mission should be handled by the MVA.

The work of the eSpace is to design the lunar camera system which will be sent to the Moon. This corresponds to the electronics (camera sensor, motherboard…), the optical system, the actuation system and the external structure.

Previous work has been done on this project to define the requirements of the mission, and the electronic part is currently being developed.

In this semester project, the first part consists of the design of the optical unit. The actuation system is then developed. And finally, several preliminary designs of the system are realised.

A second option (annex 7), where the mission is in orbit around Earth, is also considered in case the Payload 1 project does not come to an end.

2. Optical parameters

The first part of this project aims at finding the lens which will be used to capture images of the Earth. The requirements defined by the MVA can be turned into parameters specifications for the lens (annex 1 and annex 2). These parameters are
The different physical/optical requirements to ensure the desired result: a clear image of the Earth (with the lunar horizon in the foreground for case 1).

A. Angle of view

Firstly, the appearance of the Earth on the image must meet the following requirements: it shall appear entirely and its diameter should be larger than 400 pixels (annex 2).

The sensor used for the camera is the Mega X, it has two independent sections of 1024 x 500 pixels (ref 1 and annex 3), that is a square of about 1 Mpx. From this, the minimum and maximum Earth size on the image can be defined.

For the minimum case, the Earth diameter is 400 pixels (left picture of figure 1). This means that the diameter corresponds to 40% of the image width. Assuming the Earth is a circle, it is represented by about 126 kpx which is 12.6% of the image.

Then, for the maximum case, the Earth diameter is 100% of the image width, that is 1000 px (right picture of figure 1). The Earth now corresponds to 785 kpx, 78.5% of the image.

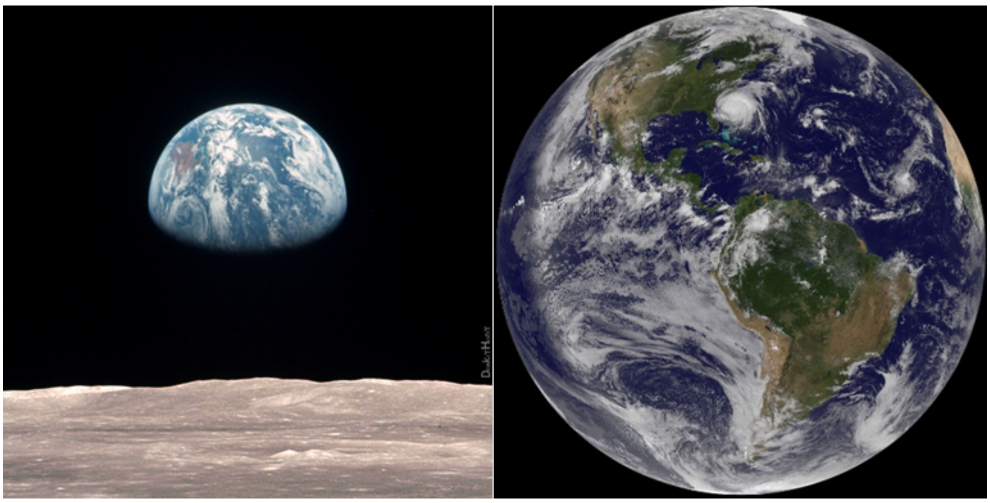

Figure 1: Preview of Earth image for the the minimum (left) and maximum (right) case

These two extreme cases define the compatible range for the Earth diameter to meet the size requirement. The next step is to obtain the angle of view for this range of size. The angle of view (AOV) defines camera frame at the distance Moon-Earth (figure 2)

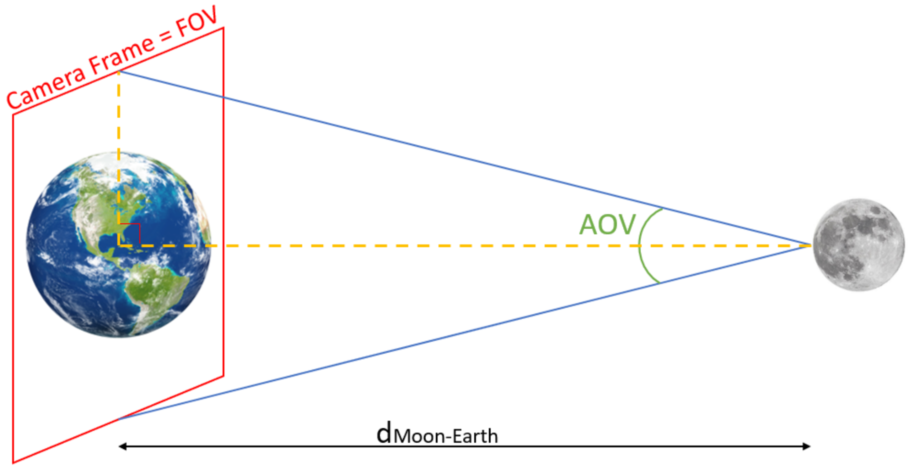

Figure 2: Scheme of the angle and field of view

The angle of view can be expressed as follow:

$$AOV = 2 \cdot arcsin(D_{Earth}/(2 \cdot \alpha \cdot d_{Moon-Earth}))$$

With $D_{Earth} = 12\,742\ km$ the diameter of the Earth, considered as a sphere,
$d_{Moon-Earth} = 385\,000\ km$ the distance Moon-Earth, assumed to be constant,
$\alpha = D_{Earth}/h_{image}$ the ratio between the Earth diameter and the image height, $0.4 < \alpha < 1$ corresponding to the extreme cases defined previously.

The relation between the angle of view and the apparent Earth diameter size on the image is plotted in figure 3. The angle of view varies from 4.74° for the minimum diameter size of 400 pixels, to 1.90° when the diameter is equal to the image width.

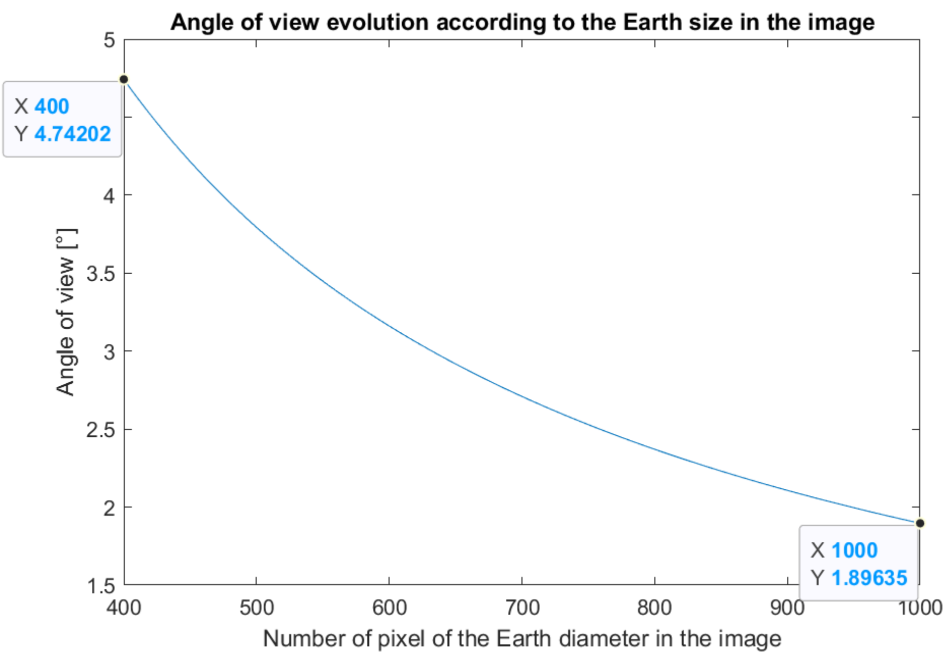

Figure 3: Graph of the Angle of view vs the Earth diameter size

However, depending on the actuation system used to track the Earth, the maximum value for the Earth diameter can probably be lowered to ensure the Earth is always seen entirely. Indeed, having a portion of space next to the Earth in the image provides flexibility for the actuation system.

B. Field of view

Once the angle of view is known, the field of view can be obtained. The field of view (FOV) is the side dimension of the area captured by the camera, at the working distance it corresponds to the camera frame (figure 2) .

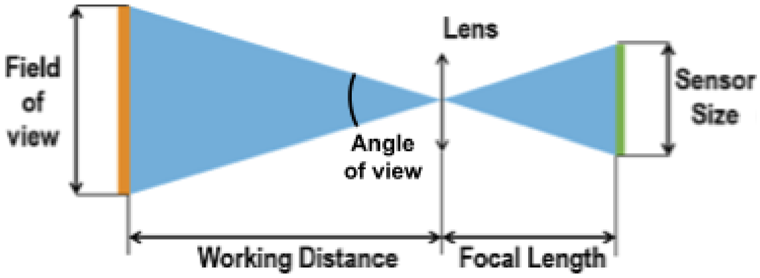

Figure 4: Scheme of the optical system [2]

From figure 4, the field of view is:

$$FOV = 2 \cdot tan(AOV/2) \cdot Working\ Distance$$

In our case the $Working\ Distance$ is the distance Moon-Earth ($d_{Moon-Earth} = 385\ 000\ km$) which leads to:

$$FOV = 2 \cdot tan(AOV/2) \cdot d_{Moon-Earth}$$

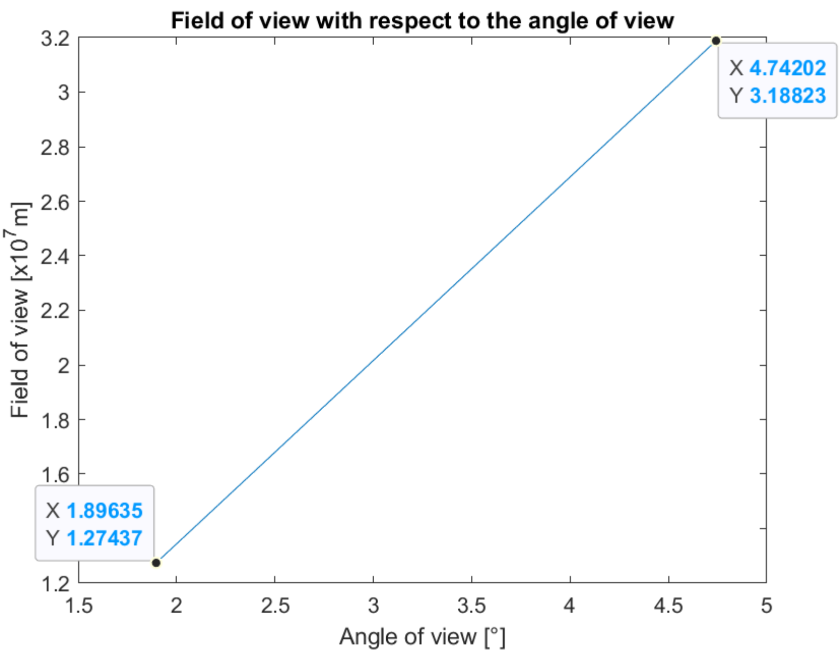

Figure 5: Graph of the field of view vs the angle of view

The resulting graph is shown in figure 5. The lower limit of the field of view, reached for the minimum angle of view, is $1.27 \cdot 10^7\ m$ which is the Earth diameter. The upper limit is $3.19 \cdot 10^7\ m = 2.5 \cdot D_{Earth}$ and is for the maximum angle of view.

C. Focal length

Finally, the focal length can be computed. The focal length is the distance between the lens and the sensor. It depends on the sensor size which is a square of 11mm width (annex 4). Because the field of view was considered to be the side length of the camera frame and not its diagonal, the dimension taken for the sensor also has to be the side length.

The formula for the focal length is the following (Thales theorem applied in figure 4):

$$f = Sensor\ Size \cdot Working\ Distance / FOV$$
$$f = Sensor\ Size \cdot d_{Moon-Earth} / FOV$$

The graph below (figure 6) gives the range of focal length possible for the lens. The focal length shall be between 133 mm and 332 mm.
One criteria to reduce the range of focal length could be to consider the total size for the lunar camera system. Indeed a requirement for the maximum system size could give an upper limit for the focal length.
Unfortunately the MVA has not given such requirement yet, then as a precaution the focal length should be low to minimise the system size, about 150mm.

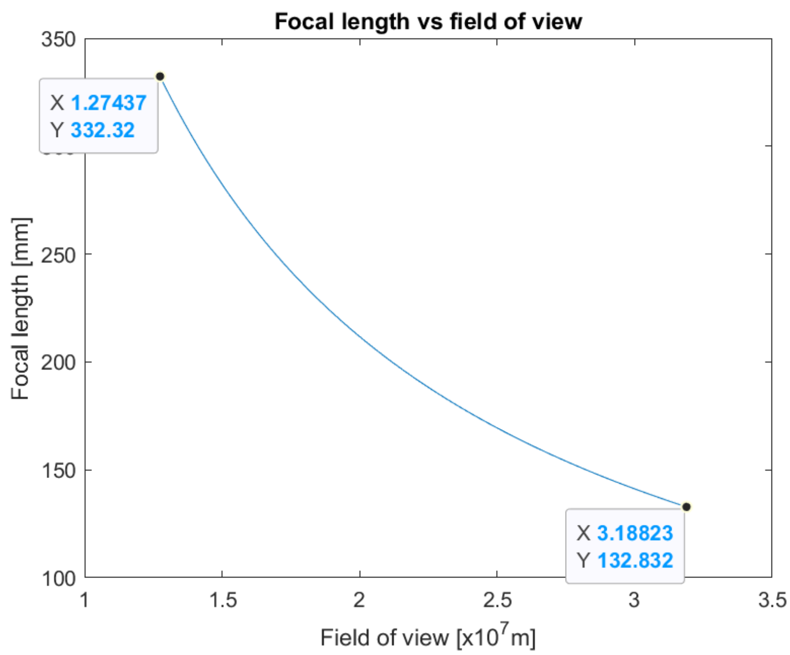

Figure 6: Graph of the focal length vs the field of view

3. Lens selection

Now that the optical parameters are defined, the next step is to select the lens for the lunar camera. The chosen lens shall met several criteria:

- Its focal length is within the range defined previously,
- The lens can withstand the temperature variations described in the requirements (annex 3)
- The lens can resist the environmental conditions encountered during the mission

This last category is unfortunately not defined in the requirements, but the conditions which should perhaps be considered are:

- The space radiation (ref 3) during the travel to the Moon and on its surface. These radiations may alter the optical properties, structural resistance of the lens.
- The lunar dust, in particular during landing, which may come in contact with the lens. It should be possible to use an aperture or to keep the lens protected during this critical period.
- The launch/landing vibrations. During these two phases, the lens may be subject to high forces and stresses which could damage it. These forces/stresses depend on the type of launcher/lander used. (annex 5 for examples of acceleration experienced by payload during take-off)

A. Lenses from past missions

The first attempt to find a lens is to look at lenses/cameras used in previous lunar missions. Indeed, this should ensure that most of the requirements (temperature variations and environmental conditions) are met. The only selection criterion is then the focal length.
Two cameras from past missions are considered in this part: one with two lenses from the Apollo missions and one from the Kaguya lunar orbiter.

Apollo missions camera

During the Apollo missions, the camera used was a Hasselblad 550C medium format. Two different lenses were used: the 70mm Hasselblad and a Zeiss Sonnar 250mm (figure 7).

The 70mm Hasselblad was used for close up photos. Its focal length is too small and does not meet the requirement.

Figure 7: Hasselblad 550C with a 70mm lens on the right and Zeiss Sonnar 250mm f/5.6 on the left/middle [5]

The Zeiss Sonnar 250mm f/5.6 was used to take photos of the Earth from the Moon (figure 8).
Even though its focal length is 250mm, the camera has a medium format sensor which means that it does not zoom as much as what is required. From figure 8, the Earth diameter is less than 15% of the image width (corresponding to an angle of view of about 13°) whereas the minimum acceptable size is 40%.
A possible solution could be to use the Zeiss Sonnar 250mm with the MegaX sensor but then the size would be large compared to the 150mm target.

Figure 8: Earthrise picture taken during the Apollo 8 mission by B. Anders [6]

Kaguya lunar orbiter camera

The second camera is the HDTV camera (figure 9) used in the Kaguya lunar orbiter (japanese spacecraft). The camera took the photo in figure 9.
Similarly as the Apollo camera, the angle of view is too wide (around 15°) and the Earth diameter is only 13% of the image width.
Moreover, this camera weighs 16.5 kg which is too heavy for the lunar camera.

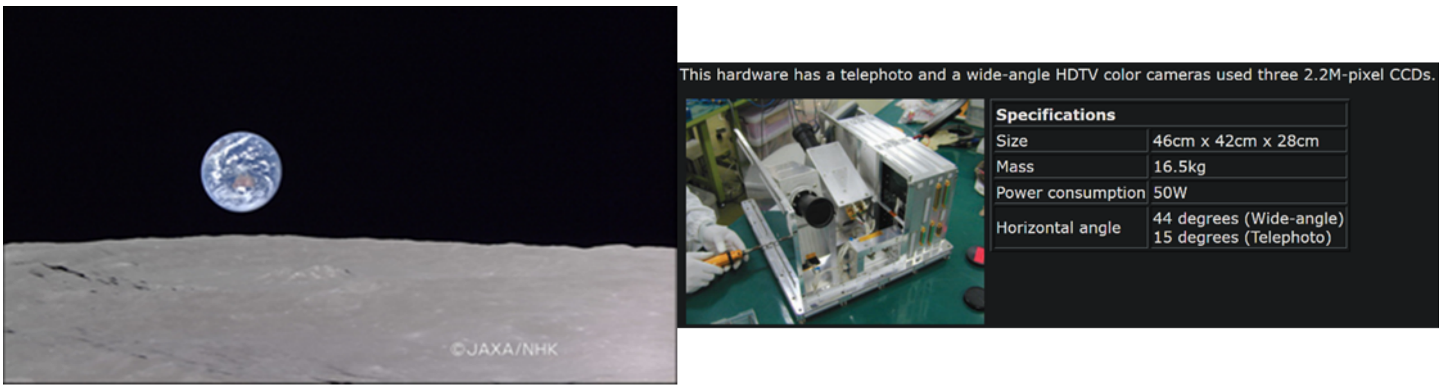

Figure 9: HDTV camera in the right and photos of the Earth shot by it on the left [7]

The cameras chosen do not really correspond to the lens expected for the system. This can be explained by the low number of lunar missions aimed at taking photos of the Earth and by the use of the MegaX sensor.
Indeed, the MegaX only has a definition of 1 Mpx which means that to meet the requirement of 400 px for the Earth diameter, the image must be “very zoomed in” with a narrow angle of view of less than 5°.
As a comparison, images of the MegaX taken with the same angle of view as the photos from past missions (figure 8 and figure 9) would have less 150px for the Earth diameter (figure 10). This is less than half of the lower limit defined.

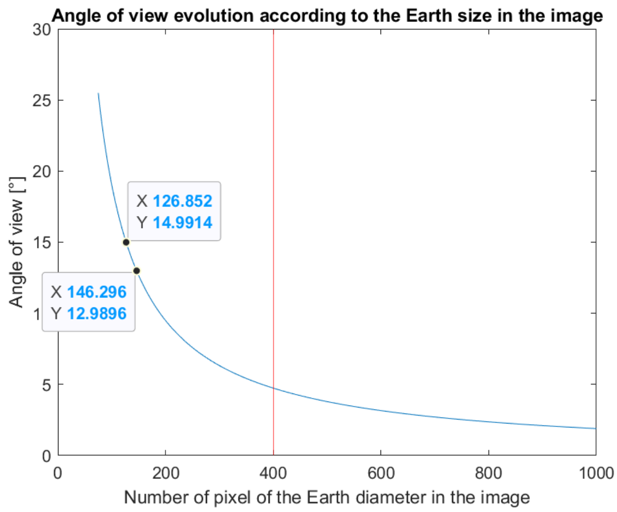

Figure 10: Comparison graph of past missions cameras vs MegaX
(the points at Y=15° and at Y=13° correspond to the Kaguya and Apollo cameras respectively)

B. Off-the-shelf lenses

The first attempt to find a lens from past missions did not work. Then the next option is to look for off-the-shelf lenses (not already used in space) which could meet the requirement. To narrow the search, the format should first be defined.

Several types of sensor exist, each corresponding to a specific image format. The goal is to find a lens designed for the closest format. The MegaX sensor is a square of 11mm width, the closest formats are the one inch (1”) and the micro four third (MFT).
The dimensions and diagonal of these sensors are listed in table 1.

Sensors	Dimensions	Diagonal
MegaX	11 x 11 mm	15.56 mm
1”	13.2 x 8.8 mm	15.86 mm
MFT	17.3 x 13 mm	21.64 mm

Table 1: Dimensions of the sensors

Although the 1” sensor is the closest to the MegaX for the diagonal length, its small side is smaller than the MegaX width. This means that part of the MegaX may not capture light (depending on how the lens mount is designed). In figure 11, part of the area corresponding to the MegaX is not covered by the 1” sensor. The circle around is the area captured by the lens (designed for a 1” sensor).
Also, the 1” is not widely used in photography and no lens with a suitable focal length could be found.
Thus, the lens sought shall be designed for the MFT sensor.

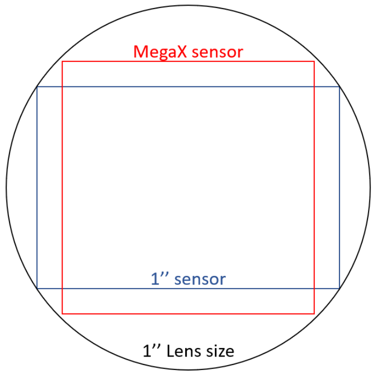

Figure 11: Scheme of the MegaX and 1” sensors

A lot of MFT lenses match the search with focal lengths of at least 150 mm (annex 6, ref 8 and ref 9). However, as there are no further requirements for the lens yet, the Olympus ED 40-150mm (ref 8 and figure 12) is selected among the other lenses.
A trade-off table (table 2) was done to compare the selected lens and what a custom lens could offer.

Type of lens	Performances	Specifications
Off-the-shelf lens: **Olympus ED 40-150 mm**	+ Variable focal length and refocus may be possible (would need an extra mechanism) + Already tested and approved + No chromatic aberration +/- Tested on Earth but not in space - Not optimised	+ Lens mount already exists + Price + Time, quickly available - Weight, heavier (several lenses) - Format is not optimal for the MegaX - If refocus, need extra mechanism => more complex and another failure parameter
Custom lens	+ One precise and fixed focal length + Optimised - Not tested yet - chromatic aberration ? TBD	+ Weight + Optimised format + Can be space grade - May need to design the lens mount - Price - Time, to produce and obtain it

Table 2: Trade-off table between the off-the-shelf and a custom lens

From this trade off method, the off-the-shelf lens is selected for the first draft. It is more convenient (already exists) and it is a good approximation (in terms of dimensions/weight for the optical subsystem) to go further into the design process.
However, for the final draft the off-the-shelf lens may not be the most optimal solution, given that a custom lens could be designed to “perfectly” fit the requirements.

Then, the lens which is used for the next steps of the project is the Olympus ED 40-150mm (figure 12) and its focal length is considered to be fixed at 150 mm, corresponding to an angle of view of 4.2°. The size comparison of the MegaX and the MFT sensor designed for this lens is shown in figure 12.

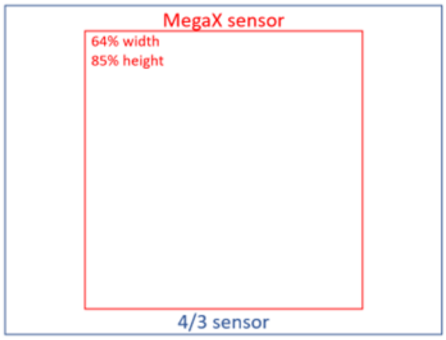

Figure 12: The Olympus ED 40-150mm on the left and size comparison of the sensors on the right

To conclude this part, a risk analysis table has been established (table 3) to present the main risks for the lens. This table is only a first draft and only considers parameters known at this stage of the project. Some additional risks may be discovered further into the project and in the following iterations of the system.

Risks	Prob* (1-5)	Effects	Solutions
Temperature variation	5	Temperature variation deforms the lens system. The effective focal length changes: - small effect, still possible to obtain clear images (depth of field large enough) - significant effect, blurred image	-Refocus for Sunlight and Eclipse -Control the temperature of the lens (insulation…) -Use another lens
Launch vibrations	2	The vibrations during launch damages the lens: - break the lens - break the lens mount - detach the lens from the system - modify focal length (if using a variable focal length lens)	-Reduce vibrations (damping mechanisms, lens positions, configuration…) -Use another lens
Radiation	1	Space radiations damages the lens	Protect the lens (insulation…) Use a radiation resistant lens
Dust (during/after landing)	4	Lunar dust covers the lens system: - photos are affected - dust blocks/prevents from refocusing	-Aperture mechanism to protect the lens from dust during landing -Cleaning mechanism of the lens (air blow…)
Other ?	?	Lens non operational Casing damaged, no actuation possible…	?

Table 3: Risk analysis table of the lens during the mission (*Prob stands for probability of the risk)

4. Actuation

The optical system defined, the actuation system can now be designed. The actuation system is composed of two actuators, one for elevation and one for azimuth, which ensure the full tracking of the Earth during its cycle. Several parameters required to select the actuators are defined in this part.

A. Range of motion

Firstly, the range of motion of the actuators should allow to track the Earth at any time from the Moon's surface. The Moon is always showing the same side to the Earth which means that the Earth remains about in the same spot.
However due to a phenomenon called "libration" (ref 11), the Earth position is not fixed. From the Moon's surface, it describes an ellipse during a cycle of 27.3 days (one lunar day). This ellipse is shown in figure 13, at any time of its cycle the Earth remains inside a 15.5° diameter circle.

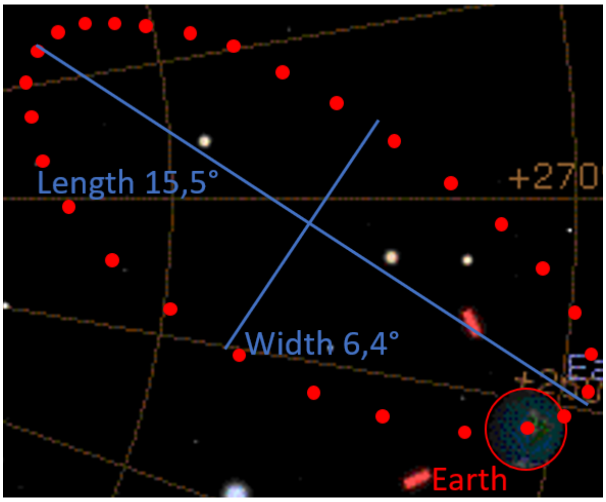

Figure 13: Trajectory of the Earth observed from the Sea of Tranquility on the Moon
(The position of the Earth each day is represented by a red dot) [10]

It appears that the main criteria for the range of motion is not tracking the Earth but orientating the camera towards it after landing (as the position of the lander is not known). This means that the range of motion of the actuators has to be higher than 15.5°. As a precaution, the two actuators shall cover a semi-sphere of rotation. The two possible configurations are presented in figure 14.

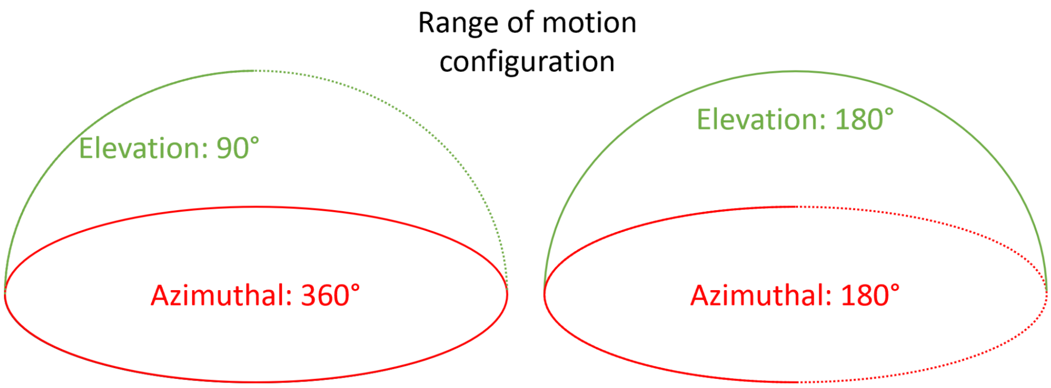

Figure 14: Configurations of the actuators to cover a semi-sphere of rotation

B. Resolution

The second parameter is the resolution (or step angle), it is the smallest possible rotation of the actuator.
The maximum acceptable resolution (figure 15) to guarantee that the Earth is always seen entirely in the image is:

$$R_{max} = AOV - AOV_{Earth}$$

Where $AOV_{Earth} = 2 \cdot arcsin(D_{Earth}/(2 \cdot d_{Moon-Earth}))$ is the angle of view corresponding to the Earth from the Moon.
Then, the maximum resolution is:

$$R_{max} = 4.2° - 1.9° = 2.3°$$

However, this resolution of 2.3° is for the extreme case where the camera only moves when the earth starts to leave the picture.
It would be better to take lower values to maintain the Earth at about the center of the picture at all times.

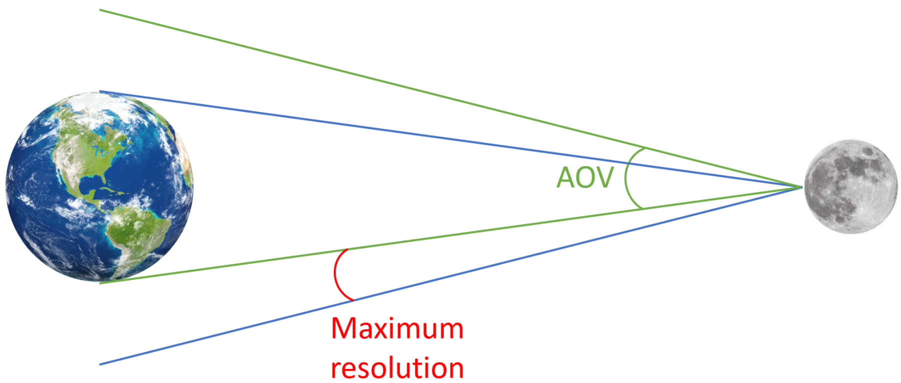

Figure 15: Scheme of the maximum resolution for the actuators

Another interesting value is the image proportion covered by one step angle of the actuators (i.e: a resolution of 1° corresponds to an image proportion of about 25%, meaning that it requires 4 step rotations to totally move the picture).
This relation between the actuator resolution and the image proportion is shown in figure 16.

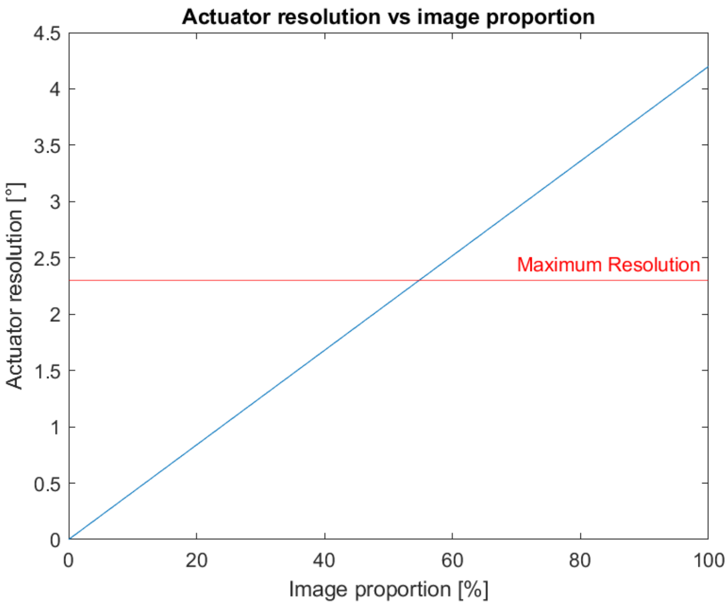

Figure 16: Graph of the actuator resolution vs the image proportion

C. Actuators position

The position of the actuators, especially for the elevation, has to be defined. Depending on its location, the required torque and the volume occupation can vary.
The actuator can be placed anywhere on the center line. However two positions can be noticed, they correspond to the lowest torque and lowest volume occupation (figure 17)
For this system, given that the torque is rather small (part Required torque) the best option is to have the actuator located near the base.
Thus, the range of motion produces the lowest volume occupation inside the casing (lowest displacement of the breakout board).
About the azimuthal actuator, the best position is under and aligned with the centre of the actuated mass when the lens is vertical.

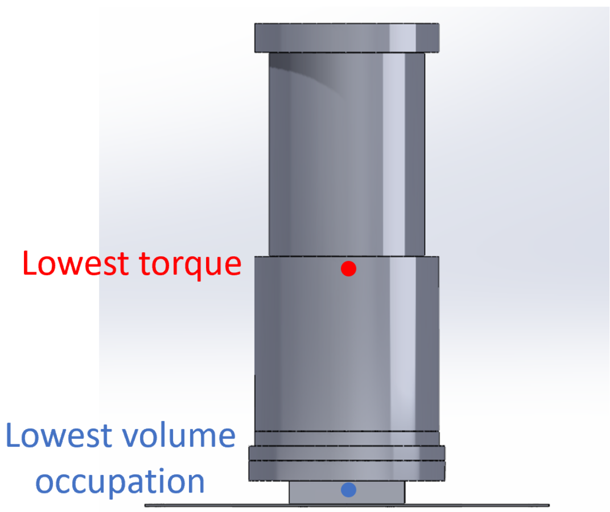

Figure 17: Positions for the elevation actuator

D. Required torque

The next parameter is the required torque. To obtain it, the actuated mass and the inertia first have to be estimated.

Actuated mass

The actuated mass corresponds to the mass of the moving parts which are:
- The lens, 150 mm long, 64 mm diameter and 190 g
- The breakout board 80x80x1 mm and 50 g, dimensions may change
- The MFT mount, 20 mm long, 64 mm diameter and about 60 g (rough estimation)

The total actuated mass is then 300g. A margin will be taken for the value of the torque to consider the extra elements not considered in this value (wires, actuator weight, insulating walls...).
Note that the motherboard and the two FPGA are assumed to be fixed in the system and therefore are not considered in the actuated mass. The breakout board is connected to the motherboard with wires and is therefore independent (motion is possible).

Estimation of the inertia

1. Lens+mount adapter = cylinder 170x64 mm and 250 g:

$$I_{Cylinder-side} = \frac{1}{12} \cdot m \cdot (3 \cdot r^2 + h^2) = 6.66 \cdot 10^{-4}\, kg.m^2$$

2. Breakout Board = square plate 80x80x1 mm and 50g:

$$I_{Plate-x/y} = \frac{1}{12} \cdot m \cdot (h^2 + d^2) = 2.67 \cdot 10^{-5}\, kg.m^{-2}$$

3. Total Inertia with the axis of rotation at the base, corresponds to the worst case with the highest torque.

$$I_{Base} = I_{Plate-x/y} + I_{Cylinder-side} + m_{Cylinder} \cdot d^2 = 2.10 \cdot 10^{-3}\, kg.m^{-2}$$

where d=75mm is the distance from the cylinder center to the base

Torque due to gravity (elevation actuator only)

On the Moon's surface, the system is subject to lunar gravity (of $0.166 \cdot g = 1.625\, m/s^2$). This will create a torque on the elevation actuator (figure 18).

The torque due to gravity (in the worst case) is:

$$T_{gravity} = F * d = m * g_{lunar} * d = 3.66 * 10^{-2}\, N.m$$

This corresponds to the minimum torque the actuator has to provide to overcome the lunar gravity.

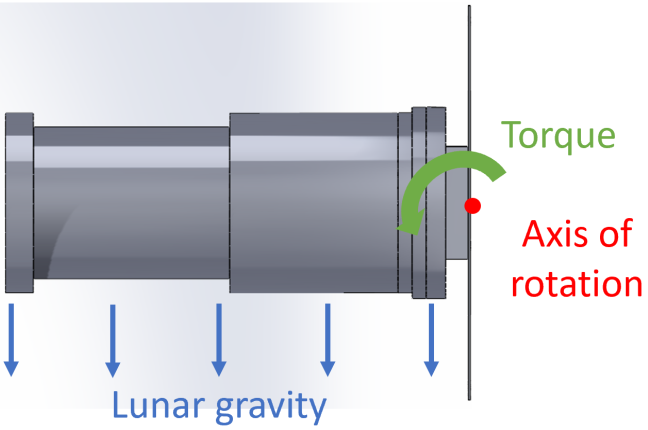

Figure 18: Schema of the torque due to gravity

Required torque for the elevation actuator

To obtain the required torque of the elevation actuator, the desired angular acceleration has to be considered:

$$T_{Angular} = I \cdot \alpha$$

I is the moment of inertia at the base and α is the angular acceleration in rad/s

In our case the angular acceleration needed is extremely low as the actuator only needs to rotate once in a while for the Earth tracking.
Assuming $\alpha = 2\pi$ (really overestimated), we obtain:

$$T_{Angular} = 2.10 \cdot 10^{-3} \cdot 2 \cdot \pi = 1.32 \cdot 10^{-2} N.m$$

$$T_{Actuator-elev} = T_{Angular} + T_{gravity} = 1.32 \cdot 10^{-2} + 3.66 \cdot 10^{-2} = 4.98 \cdot 10^{-2} N.m$$

Considering a safety factor of 2, the minimum required torque for the elevation actuator is 100 mN.m

Required torque for the azimuthal actuator

For the azimuthal actuator, the torque due to gravity does not have to be considered as the weight would be applied vertically and will not produce any torque.
On the other hand, the azimuthal actuator has a higher actuated mass (coming from the elevation actuator mass and its fixing support).
Thus, as a first estimation the required torque for the azimuthal actuator can be considered to be the same as for the elevation actuator, that 100 mN.m.

If the azimuthal actuator works as an internal gear (design 1), thus the required torque also depends on the transmission factor as follow:

$$T_{Act-\ gear} = \eta \cdot Z_{Actuator}/Z_{Outer} \cdot T_{Required}$$

Where $Z_{Actuator}$ and Z_{Outer} are the number of teeth of the actuator and of the outer gear respectively and $T_{required}$ is the torque required without internal gear, that is 100 mN.m.

E. Selection of the actuators

Finally, it is possible to select the actuators now that the parameters are defined. In this part several compatible actuators for the system are presented.

1. The MST171A02 (ref 12 and figure 19): resolution of 1.8° and a torque of 0.12 N.m.

Figure 19: Actuator MST171A02

2. The 11HS3410 (ref 13 and figure 20): resolution of 1.8° and 0.1 N.m.

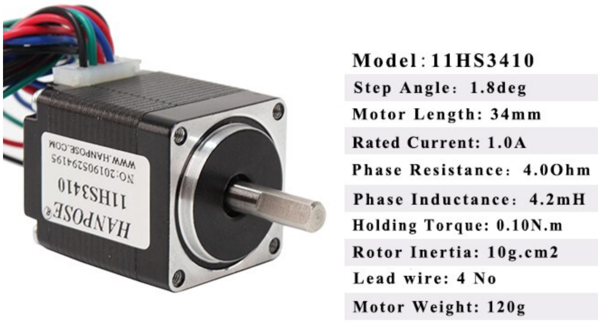

Figure 20: Actuator 11HS3410

3. The MST114A163L3AA0.7 (ref 14 and figure 21): resolution of 1.8° and 0.12 N.m.

Figure 21: Actuator MST114A163L3AA0.7

The actuators presented here are just a few among many possible actuators. They were selected because they are just above the required torque and their resolution is appropriate.
However, note that this required torque is only an estimation obtained from current datas and it may change later in the project.

F. Earth Observation for different scenario

As seen in the part Range of motion, the Earth trajectory is an ellipse when seen from the Moon surface. It is possible to use this cycle in order to optimise the capture time (time when Earth is in the camera frame) without using actuators, in order to save energy or in case of failures of the actuators. Two cases are considered to cover different scenarios.

Without actuators

This case is for when the camera is placed in one position and the actuators cannot be used.
The best for the camera is one of the extremities of the ellipse. Indeed, the Earth velocity is the smallest in these regions (higher dot concentration).
The green circle in figure 22 represents the angle of view of the lens and the green square the angle of view captured by the sensor.

In the best case, where the camera is pointing at one extremity and the sensor is well orientated (may not be possible), the camera can capture images of the Earth during around 7 days per cycle: 7/28 = **25%**

In the worst case (if the actuators stop working or run out of batteries), if the camera is looking in the middle of the ellipse, it will still be able to capture about 2.5 days every cycle: 2.5/28 = **9%**

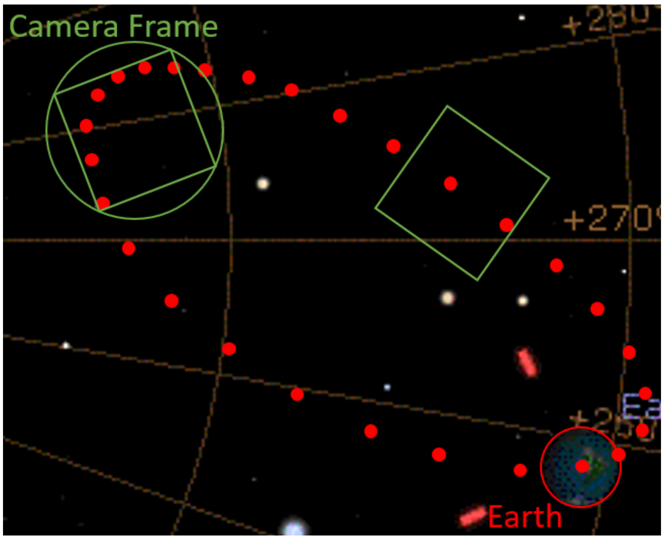

Figure 22: Scenario without actuators

With one actuator only

If only one actuator (the elevation in this case) is working (figure 23).

For the best case, where the camera is placed on the middle of the ellipse with the remaining actuator moving parallel to it, the camera can cover more than 15 days per cycle: 15/28 = **53%**

In the worst case, the camera is in the middle sliding perpendicular to the ellipse, the Earth is seen about 5 days per cycle: 5/28 = **18%**

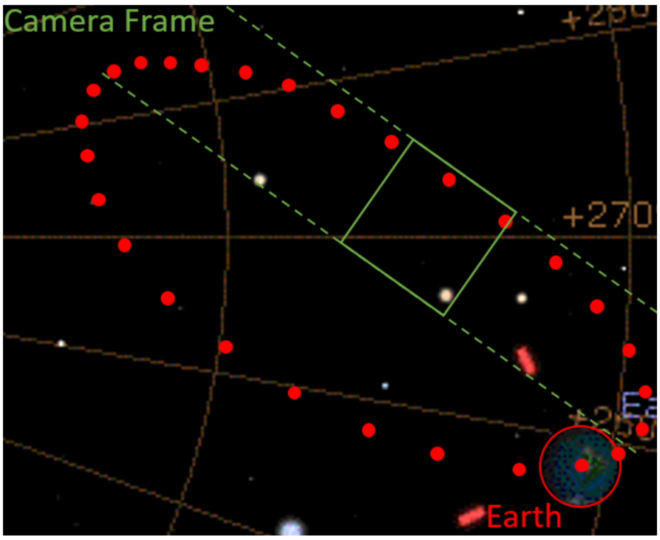

Figure 23: Scenario with the elevation actuator only

5. Design of the system

In this last part of the project, three different designs for the lunar camera system are presented. The two first designs have one actuator of each kind (elevation and azimuth) but the last one, created more recently, has two elevation actuators. The designs are realised on SOLIDWORKS.

A. Dimensions of the elements

The dimensions of the different components used for the designs are listed in table 4. These dimensions correspond to the choices made during the project: the lens is the Olympus ED 40-150mm (ref 8) and the actuators dimensions are inspired from those presented in the part Selection of the actuators.

Elements	Length	Width / Diameter	Height
Lens (1 in figure 27)	150 mm	D: 64 mm	/
MFT Mount (2 in figure 27)	20 mm	D: 64 mm	/
Chip (3 in figure 27)	11 mm	11 mm	2 mm
Breakout Board (4 in figure 27)	80 mm	80 mm	2 mm
Motherboard (2 in figure 24)	140 mm	140 mm	10 mm
FPGA x 2 (1 in figure 24)	105 mm	70 mm	10 mm
Elevation Actuator (figure 26)	42 mm	42 mm	24 mm
Azimuthal Actuator (figure 25)	50 mm	30 mm	24 mm

Table 4: Dimensions of the components used in the designs

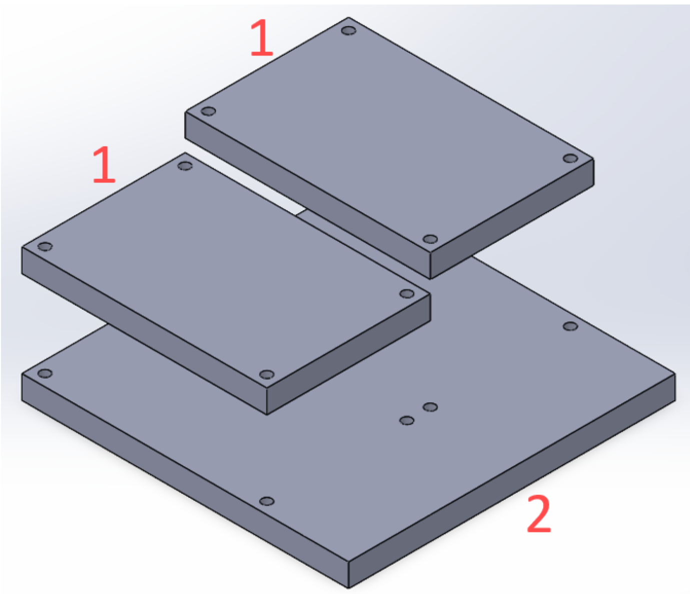

Figure 24: Motherboard and the two FPGA

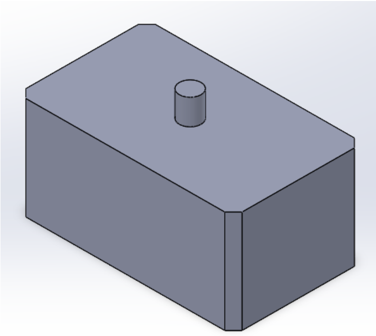

Figure 25: Azimuthal Actuator

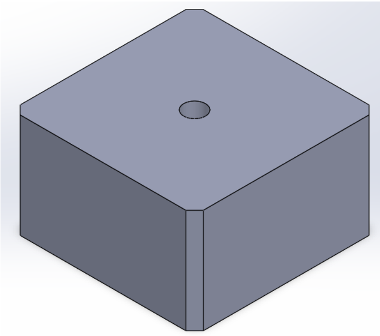

Figure 26: Elevation Actuator

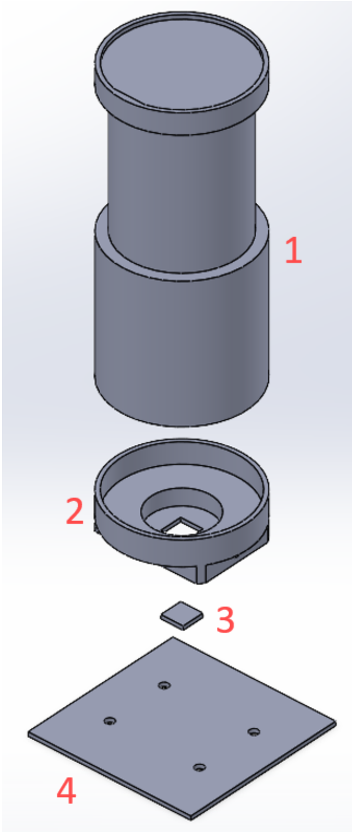

Figure 27: Four components of the designs

B. Design 1: Dome

For design 1, the structure is composed of a dome containing/holding the rotating elements (lens, breakout board…). It gives protection to the internal elements (the dome is acting as an insulating wall) from the exterior.
Two actuators are used to point the camera, one for elevation and one for azimuth.

First draft

The dome part is inspired by the design of observatories (figure 28).
The dome with all the elements inside rotate together thanks to the azimuthal actuator. The mechanism between the azimuthal actuator and the dome corresponds to an internal gear.
A slot in the dome allows the lens to move vertically and to cover 180° of rotation with the elevation actuator.
Below the dome is the base, in which the fixed elements are located (motherboard, FPGA,...).

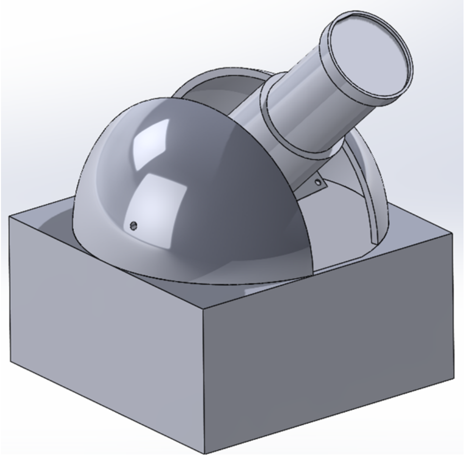

Figure 28: First draft of the Dome design

Second draft

The design has been improved in the second draft (figure 29).
The dome is smaller and its shape has been adapted to reduce the weight and volume occupation.
A cover rotating with the lens ensures that the volume inside the dome is always insulated.
The elevation actuator is located inside the dome and drives a shaft connected to the lens.
The azimuthal actuator is fixed on the base and allows the dome to rotate above it.

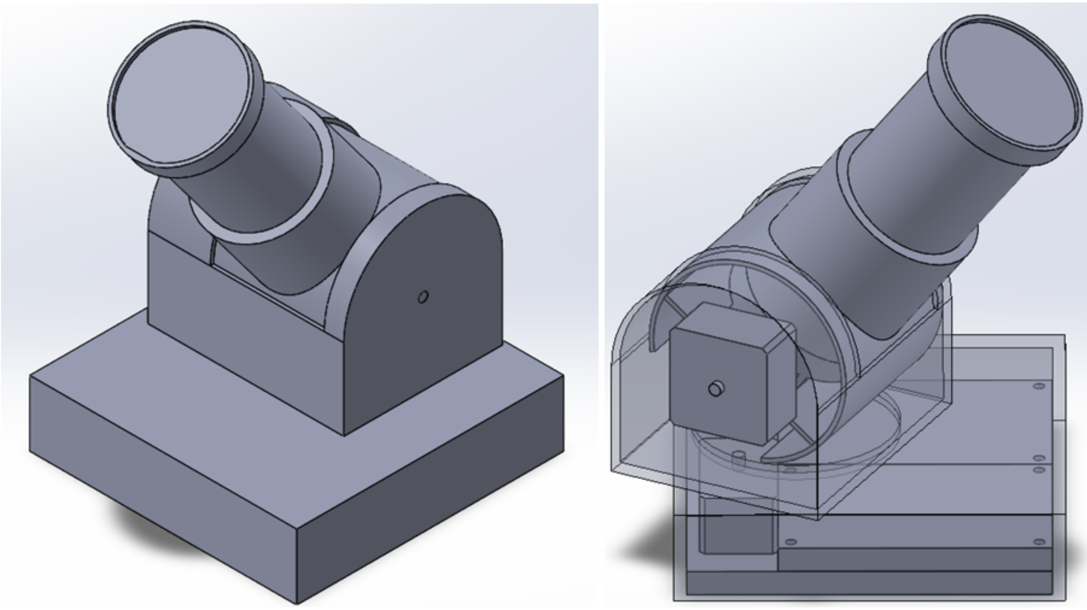

Figure 29: Second draft of the Dome design

C. Design 2: Camera Support

Figure 30: Camera Support [15]

For this design, the elements are assumed to be already protected (having their own insulation). It's then possible to get rid of the dome to gain weight and space.
This configuration of the actuators is inspired by a camera support (figure 30).
The elevator actuator is the same as before (same position, range of motion…)
However the azimuthal actuator is now directly holding the moving part, it's the link between the base fixed and the lens (+elev actuator + sensor…) moving.

First draft

For the first draft, the vertical axis allowing azimuthal motion is placed on the middle of the base. The base is rather big because of the unknown dimensions of the electronics (figure 31).

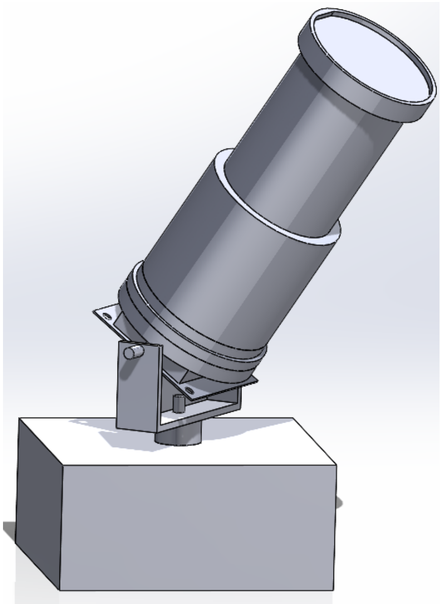

Figure 31: First draft of the Camera Support design

Second draft

In the second draft (figure 32), the vertical axis is moved on one side to reduce the volume occupation in “safe mode” (when the lens is horizontal). This “safe mode” also provides a support for the lens to reduce the forces on the actuators during launch/landing.
The dimensions of the base have been adapted to the new electronics dimensions.

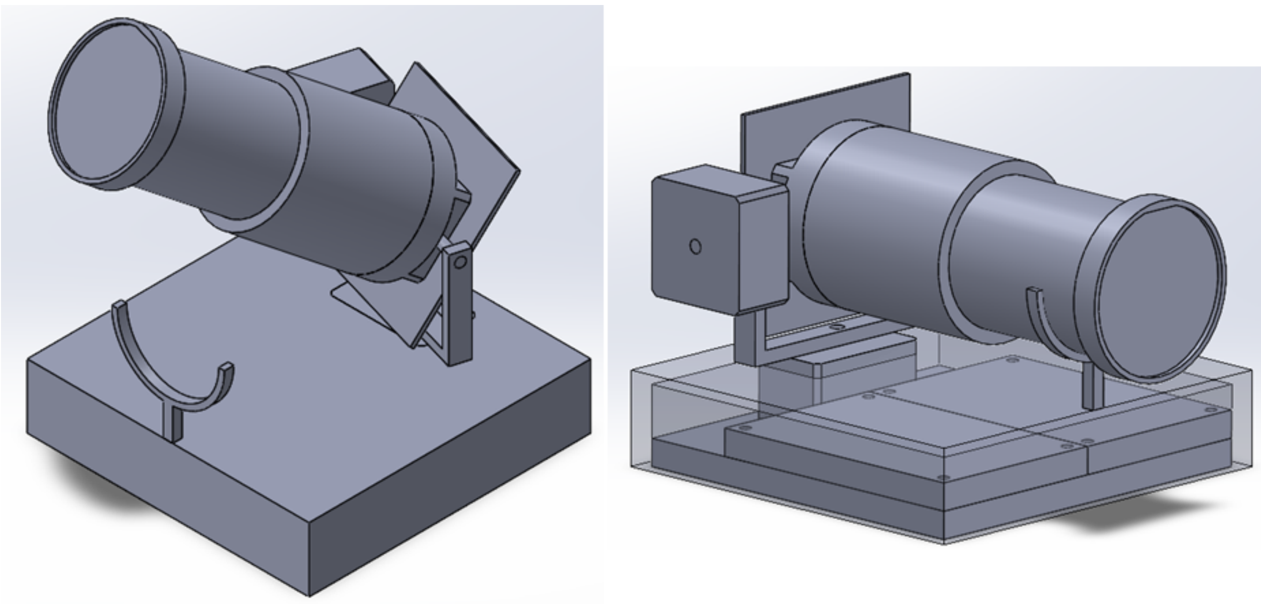

Figure 32: Second draft of the Camera support design

D. Design 3: Double elevation

This design (figure 33) is using two elevation actuators placed with an angle of 90°. This configuration provides the same range of motion but also allows to reduce the actuator use when tracking the Earth during its cycle.
There is only one draft of this design as it has been developed later.
Because there is no direct link (no constraint with an actuator) between the base and the rotating elements, it is possible to adjust the position to optimise the design.

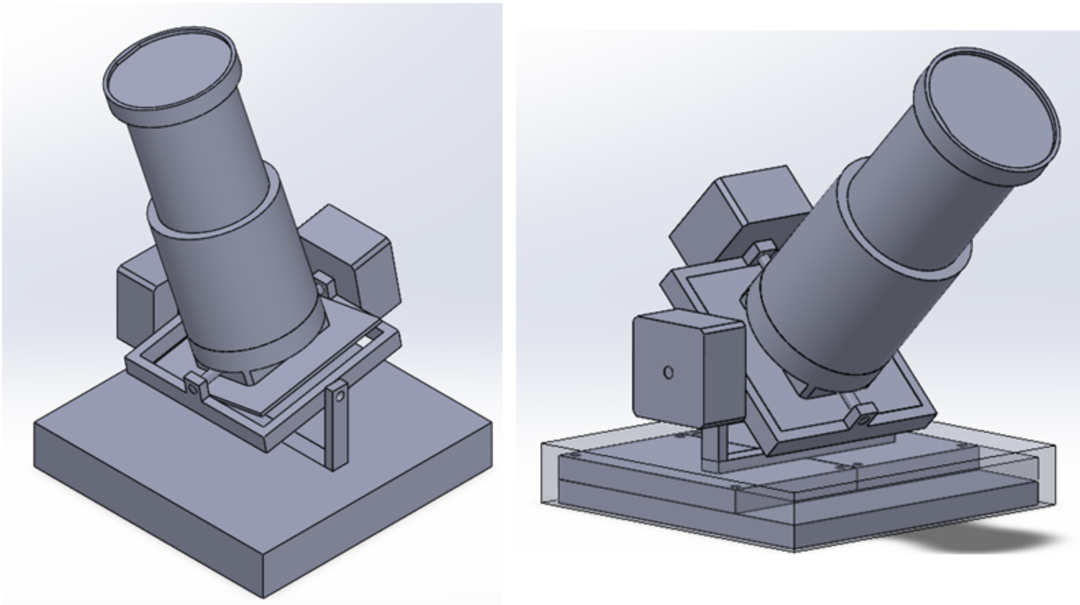

Figure 33: Double elevation design

E. Trade-off table of the different designs

Finally, the trade-off table (table 5) below compares the different designs presented previously. This table only considers the aspects known to date, and is likely to change when the designs will be improved.

Designs	Pros	Cons
1. Dome	+ Provides high protection of the internal elements with its insulation + Direct link between the dome and the base to connect elements (wires…) + Strong structure (actuators well fixed) which may withstand large stresses/vibrations/forces	- Large volume occupation - Most heavy design - Larger torque required on the azimuthal actuator due to the dome mass
2. Camera Support	+ Includes a “safe mode” with minimum volume occupation and reduced stresses on the actuators + More compact than 1 + Good compromise weight/resistance for the structure	- No protection for the internal elements - May be hard to connect wires from the base to the breakout board
3. Double Elevation	+ Reduced use of the actuators by combining 2 elevation motions + Light design + The position of the optical system can easily be modified	- No protection for the internal elements - Weakest structure - May be hard to connect wires from the base to the breakout board

Table 5: Trade-off table of the different designs

Anyway, for all the designs the dimensions may be improved depending on the future updates on the components dimensions and on the mission requirements. These designs mostly focused on the actuators configuration to provide the required range of motion, as well as on reducing the actuated mass moved by the actuators.

In all the designs, the base has been sized to only include the current electronics, but it can still be enlarged to contain other elements such as batteries, heat controller, …

6. Conclusion

During this project, four main parts have been covered. It is important to note that for each of them, several assumptions and personal choices have been made to overcome the problems and the lack of information (especially about what the MVA wants and requires).

Although these assumptions and choices may change in the future, when more information will be available, the results obtained still provide a fairly reliable estimate of the different parts of the system.

The main limitations encountered during this project are chronologically:

- The lack of specifications for the required lens. Once the focal length and image format are defined, there were no real other criteria to refine the selection: no dimensions, price, weight values. And the environmental conditions, that the lens shall resist, are hard to define without further information about the launcher, lander, landing site…
- Also, for the lens it was not clear if a refocus is needed on the Moon: after landing and between sunlight and eclipse. If yes, then a focus mechanism will have to be implemented
- For the actuation part, the values considered only take into account the optical unit and the electronics. The weight of the structure/wires was not known.
- For the design, the elements considered are only the ones defined previously in the project (optical and actuation systems) and the electronics. There was no information on the other elements which may be present: an energy system (batteries or using energy from the lander?), a temperature regulator (to cool or heat or both?), insulating walls, a communication system…

Anyway, even with these limitations it was possible to obtain results for each part. During the following developments and iterations of the system, it is likely that these problems can be solved. Some ideas on the future that can be done to advance the project are:

- Improve the designs and create a prototype (3D printing…) to see if it works: checking the actuators configuration/range of motion, volume available for all the components… And why not, try to track the Moon from the Earth!
- Define more precisely the different parts: can the lens chosen resist in space, the launch…?, iterate the values for the actuators by considering the weight of the structure and other components.
- Resume work on the second option (annex 7), mission from Earth orbit, in case the first one does not come to fruition (during the semester, the goal of the mission for the second option was not found, and it was put aside in order to focus on the first one).

Overall, this project was a great opportunity for me to work on a lunar mission. It was really exciting and I hope this project will be successful.

Thanks to David for his precious help and advice all along the project !
And to Minglo for his help on the electronic part !

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Annex

	Functional Requirements
R-Func-001	The payload shall record a minimum of 1 true color image of Earth from the lunar surface before the misison end
R-Func-002	The payload shall autonomously point at and locate the Earth within the image frame.
R-Func-003	The payload shall have visibility of the lunar horizon during operations.

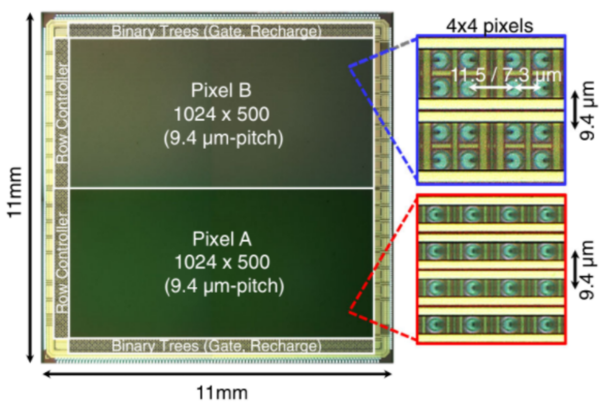
Annex 1: Functional Requirements for the Lunar Camera [16]

R-Perf-002	The Earth shall appear entirely in the image and its diameter within the image shall be of at least 400 px

Annex 2: Requirement for the Earth’s appearance on the image [16]

R-Env-Temp-001	The payload shall withstand temperature range of -30°C to +50°C during flight and on the surface
R-Env-Temp-002	The payload shall withstand temperature range of -40°C to +60°C during flight until touchdown
R-Env-Temp-003	The payload shall withstand temperature range of -50°C to +60°C after touchdown on the surface
R-Env-Temp-004	Payload own thermal control shall be passive

Annex 3: Requirement for the temperature resistance of the payload [16]



Annex 4: Sensor MegaX [1]

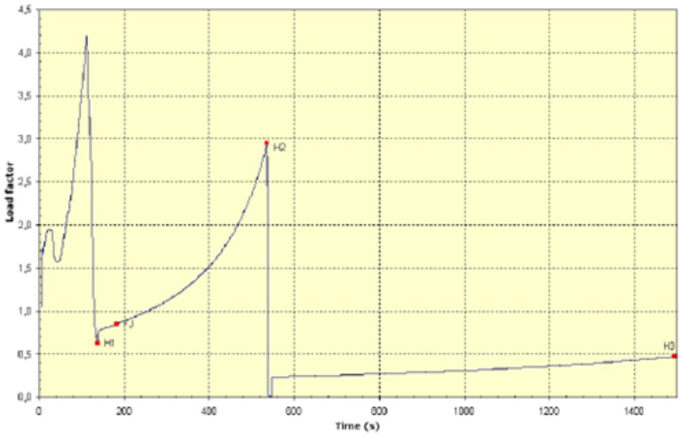


Figure 3.2.1.a - Typical longitudinal static acceleration

Minotaur I User's Guide

TABLE 4-1. PAYLOAD CG NET STEADY STATE ACCELERATION FOR A NOMINAL 800 LB STIFF PAYLOAD

Event	Axial (G's)	Lateral (G's)
Liftoff	0 ±4.6	0 ±1.6
Transonic	3.2 ±0.5	0.2 ±1.2
Supersonic	3.8 ±0.5	0.4 ±1.1
S2 Ignition	0 ±6.6	See Fig 4-2
S3 Ignition	0 ±6.1	See Fig 4-2
S3 Burnout	See Fig 4-3	0.3 ±0.0
S4 Burnout	See Fig 4-3	0.3 ±0.0

Annex 5: Examples of acceleration experienced by payload during take-off, with an Ariane 5 on the left and with a Minotaur I on the right [4]

Marque	Modèle	Focale	Ouverture Max.	Filtre	Poids
+ Olympus	40-150mm f/4-5.6	40-150mm	f/4-5.6	58mm	190g
+ Panasonic	40-150mm f/4-5.6	40-150mm	f/4-5.6	52mm	200g
+ Panasonic	35-100mm f/2.8 II	35-100mm	f/2.8	58mm	357g
+ Olympus	40-150 mm f/2.8	40-150mm	f/2.8	72mm	880g
+ Panasonic	100-300mm f/4-5.6 ASPH	100-300mm	f/4-5.6	67mm	520g
+ Panasonic	50-200mm f/2.8-4 Leica DG Vario Elmarit	50-200mm	f/2.8-4	67mm	660g
+ Panasonic	100-400mm f/4-6.3 DG VARIO ELMAR	100-400mm	f/4-6.3	72mm	985g
+ Panasonic	200mm f/2.8 LEICA DG Elmarit	200mm	f/2.8	77mm	1245g
+ Olympus	300mm f/4 PRO	300mm	f/4	77mm	1270g

Annex 6: Different compatible MFT lenses for the lunar camera

Annex 7: Case 2: Mission is from the Earth orbit

Mission from orbit

A. Picture of the Earth

What orbit ?

ISS orbit => 400 km above Earth surface

Other orbit => TBD

View of the Earth:

View of the horizon to see the curvature of the Earth

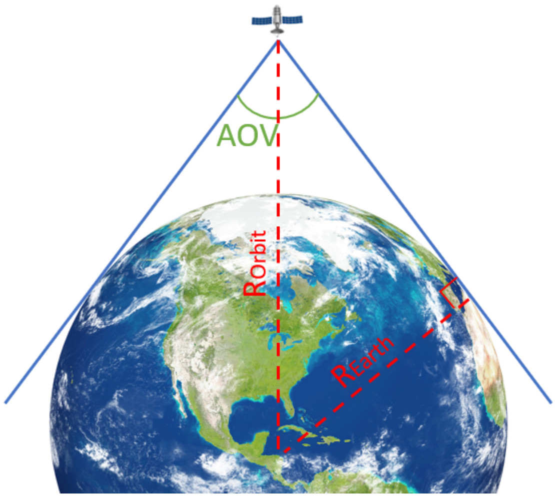
Other view : ground below the satellite, Earth + Sun (possible ?), Moon, …

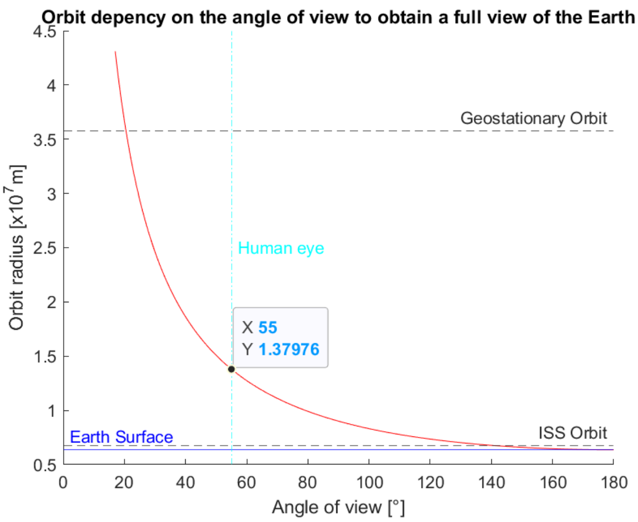
Other option:

At which orbit should the satellite be placed to have a full view of the Earth ?

Assuming the Earth is a sphere of radius R_{Earth} and that the satellite orbit is circular (can be reviewed later).

$$AOV/2 = sin(R_{Earth} / R_{orbit}) \Leftrightarrow R_{orbit} = R_{Earth} / arcsin(AOV/2)$$





The graph shows, given the angle of view, the orbit at which the satellite should be in order to have a full view of the Earth. The orbits above the geostationary altitude are not considered as this would complicate the mission a lot (cost increase, launcher complexity, …). Similarly, orbits under the ISS (?) are also eliminated as the friction with the upper layer of the atmosphere may slow the satellite and cause it to crash/be destroyed. However, the possible range of AOV/orbit left is still very large.

- A parameter that could reduce it would be to consider an AOV close to the human eye, 55°, in order to represent what a man would see without any deformation. This AOV requires an orbit of at least $1.37976 \cdot 10^7\ m$ to fully capture the Earth.

https://photodoto.com/camera-lens-closest-to-human-eye/
https://hypertextbook.com/facts/2002/JuliaKhutoretskaya.shtml

focal length = 22 mm

aperture = f/2.1 - f/3.8

Other choices are possible:

- choose the most common orbit altitude for satellite > reduce mission cost
- choose the AOV/FOV first and then adapt the orbit …

Next,

- Number of pixel of the Earth diameter on the picture
- Focal length calculation (+FOV before)

To finalise the lens choice, it is important to specify more parameters:

- What is the function of the satellite? What kind of image shall it take?
- Size of the satellite, what kind of cubesat exactly?
- Orbit preference ? w.r.t.the launching ?

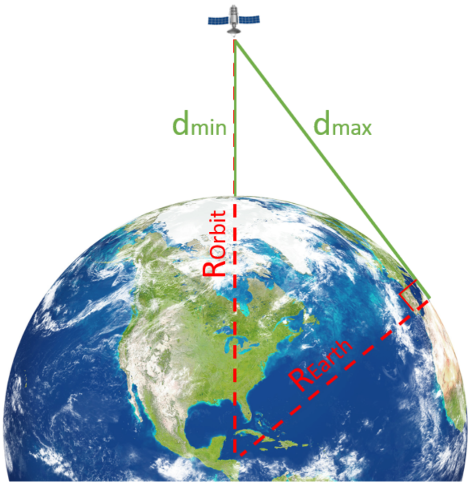
B. Image settings

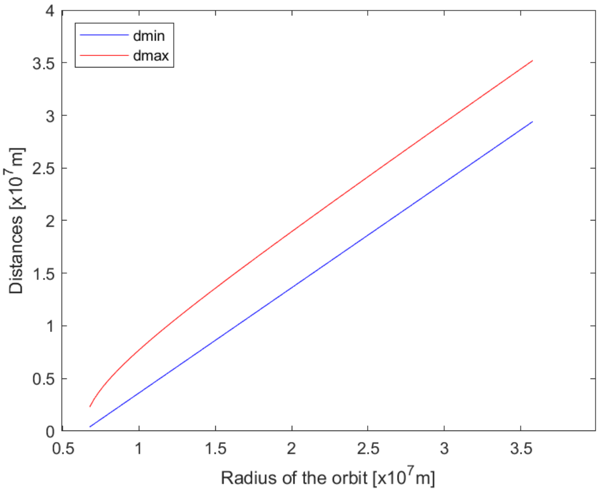
- **Distance Object-Lens/Working distance:** Distance Earth-Satellite varies from dmin to dmax.
- (Half) **Height of the object** depends on the desired size of the Earth in the picture.
- (Half) **Height of the image:** $h_i = sensor\ size/2 = 11/2 = 5.5\ mm = 5.5 \cdot 10^{-3} m$ (MegaX specs)
- **Distance Lens-Sensor** = di > TBD (di maximum value depends on the dimensions of the CubeSat 1U or 1.5 U)
- **Focal Length:** f > TBD, cf Lens parameter part

Hypothesis: Earth considered as a sphere

$$d_{min} = R_{orbit} - R_{Earth}$$

$$d_{max} = \sqrt{R_{Orbit}^2 - R_{Earth}^2}$$





Knowing dmin and dmax is important to ensure that every part of the Earth is clear on the image.

C. Lens parameter

Requires more info/specifications about the mission

D. CubeSat specifications

The goals of a CubeSat are *“to reduce cost and development time, increase accessibility to space, and sustain frequent launches.”*
“A CubeSat is a class of satellites that adopt a standard size and form factor, which unit is defined as ‘U’. A 1U CubeSat is a 10 cm cube with a mass of up to 2 kg. This standard primary objective is to provide specifications for the design of CubeSats ranging from 1U to 12U.”

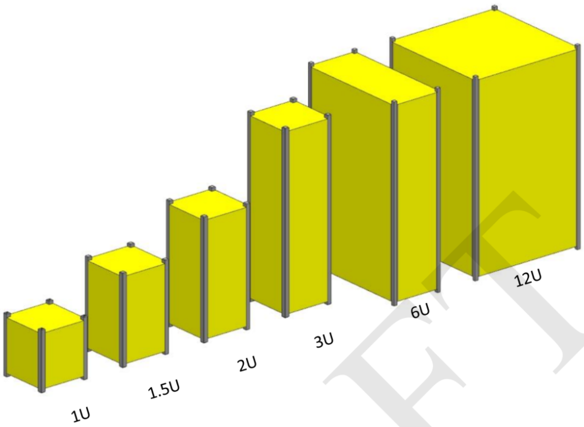


Figure 2: The Current CubeSat Family (1U – 12U)

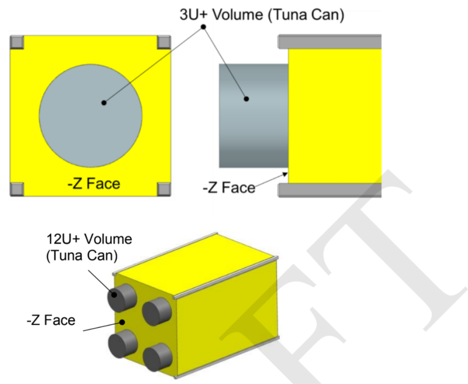


Figure 3: Optional Extra Volume shown on 3U and 12U –Z Face (also known as a "Tuna Can"). The Extra Volume is also an optional feature for the 6U configuration.

Regarding the mission, if the lens/optical system is too large for the satellite it may be necessary to use a specific type of CubeSat (see above) which allows the presence of an extra volume outside the cube. However this Tuna Can option is only available for 3U, 6U and 12U CubeSat which is not suitable for the mission, as the CubeSat used should be 1U, 1.5U or 2U maximum.

Several specifications must also be satisfied to fully comply with the CubeSat design.
- Mass requirement
- Center of gravity position

Table 1: CubeSat Mass Specifications

U Configuration	Mass [kg]
1U	2.00
1.5U	3.00
2U	4.00
3U	6.00
6U	12.00
12U	24.00

Table 2: Ranges of acceptable center of gravity locations as measured from the geometric center on each major axis

	X Axis	Y Axis	Z Axis
1U	+ 2 cm / -2 cm	+ 2 cm / -2 cm	+ 2 cm / -2 cm
1.5U	+ 2 cm / -2 cm	+ 2 cm / -2 cm	+ 3 cm / -3 cm
2U	+ 2 cm / -2 cm	+ 2 cm / -2 cm	+ 4.5 cm / -4.5 cm
3U	+ 2 cm / -2 cm	+ 2 cm / -2 cm	+ 7 cm / -7 cm
6U	+ 4.5 cm / -4.5 cm	+ 2 cm / -2 cm	+ 7 cm / -7 cm
12U	+ 4.5 cm / -4.5 cm	+ 4.5 cm / -4.5 cm	+ 7 cm / -7 cm

+ every specification listed in the CubeSat Design Specifications document.

Lens market:
Optic system
https://www.imperx.com/aerospace-cameras/
https://blog.satsearch.co/2020-03-25-optical-payloads-for-small-satellites-a-sector-overview
https://www.unitedlens.com/custom-optics/
https://www.ien.eu/article/designing-producing-specialist-optics-for-aerospace-applications/
https://www.raptorphotonics.com/products/owl-640-m/

E. Satellite mission

1) Satellite as GPS system

only 2 satellites instead of 4. Need to launch 2 satellites ?
Still need a camera or only an antenna ?
Need more info

2) Tracking space debris satellite

Is the camera definition enough for this kind of application ?
Compromise between, wide angle of view but low distance or high distance but narrow angle of view.
Software part, how important ? to recognize/track debris…?
Tessa: deploy a constellation of mini-satellites
https://computing.llnl.gov/projects/tessa-tracking-space-debris
https://aerospace.org/article/space-debris-101
Space debris size

Debris Size	Similar in size to	Mass (g) aluminum sphere	Kinetic Energy (J)	Equiv. TNT (kg)	Energy similar to	Quantity	Trackable
1 mm	medium-grit sand or poppy seeds	0.0014	71	0.0003	Pitched baseball	Tens of millions	Can't be tracked
3 mm	smaller than BBs	0.038	1910	0.008	Bullets	Millions	Can't be tracked
1 cm	blueberries	1.41	70700	0.3	Falling anvil	Hundreds of thousands	Can't be tracked
5 cm	plum	176.7	8840000	37	Hit by bus	Tens of thousands	Most can't be tracked
10 cm	softball	1413.7	70700000	300	Large bomb	Tens of thousands	Most can be tracked
> 10 cm	basketball to football field	1400 to 500,000,000	Up to 1x10^13	Up to 3,000,000	Very large bomb	Thousands	Tracked and cataloged by the space surveillance network

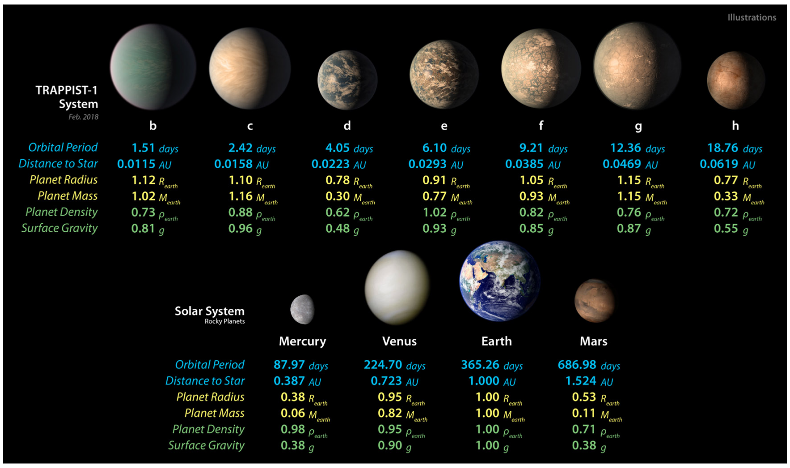
Given our sensor of 1Mpx 1000x1000 px, the maximum area which could be monitored is:
$Area = side * side = (1000 * debris\ size)^2$ in the best possible case where debris corresponding to 1px can be tracked
For a small debris of 3mm, the area would be 9m^2
For 10 cm debris, it would be 10 000m^2 = 100*100, even with this size of debris the monitored area is only 100m wide (very small in space)

Option not viable with the current sensor ?

3) Other applications that could make use of our sensor ?

- Sun/planets observation or picture without the color change due to atmospheric gas?

Sun: diameter of 1,4*10^9 m at distance of 1,5*10^11m



Given the distance/size, the camera will probably need a telephoto lens (large focal distance) thus it will be hard to fit in a small CubeSat…

- Observation of a specific place on Earth ?
- Watching the Earth horizon