NASA Space App Challenge 2018

Challenge: **Design by Nature**

PoliBeetle-7

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CHAPTER 0:

INTRODUCTION TO

PoliBeetle-7

INTRODUCTION

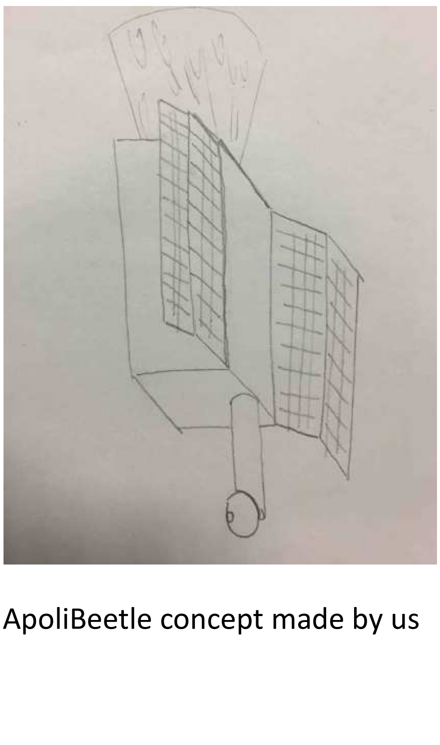
Why the name “PoliBeetle-7”?

The challenge in which we are competing asks about designing a spacecraft surface flying inspector which is created while being ispired by Nature.

Since the main purpose of this flyer was to watch the spacraft externally in the search of damages, we started thinking about what is the sight in Nature: we took relevance of the human sight, the bats ultrasounds sight and the some of insects X-rays sights. So in the search of the name we arrived at the choice of an insect name.

While designing the sensor to inspect the surface we decided to make it like a horn outside the flyer and from that similarity with the small insect, we selected the name “Beetle”. Because of the fact that we are all students of the Politecnico of Milano the prefix “Poli” does explain itself.

The full name of our flying inspector is PoliBeetle-7 and the number 7 was chosen beacaude we thought it is a beatiful and particular number: seven is the number of days, the hills of Rome and thounsands of other meanings.



Rhinoceros beetle. *Credits: e-Bay* ApoliBeetle concept made by us

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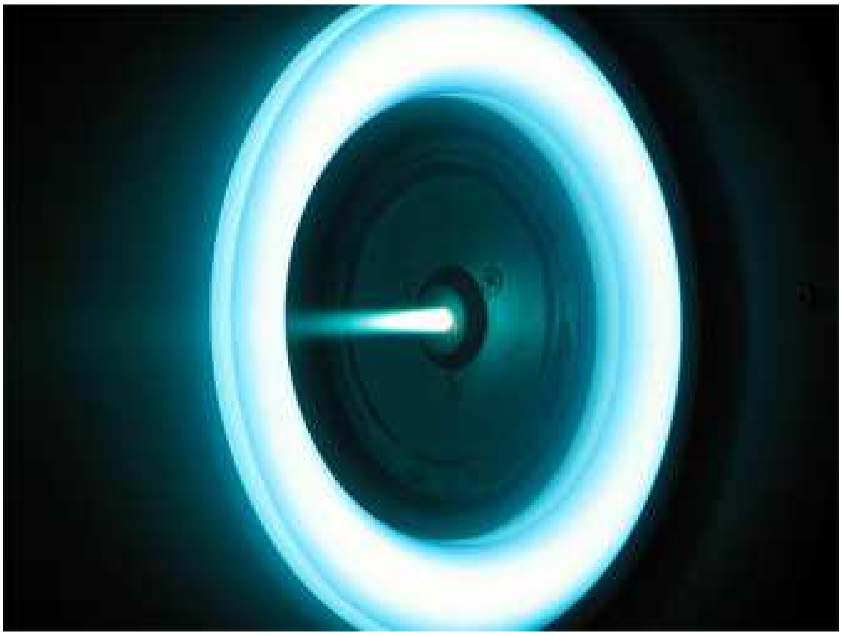
CHAPTER 1:

REPORT ABOUT THE ENGINE CHOICE FOR

PoliBeetle-7



Concept of an Ion Engine using Hall's effect. *Credits: Space News*

Abstract

The aim of this report is to justify the choice behind the selection of a determinate engine to make the PoliBeetle inspector flying around a main spacecraft.

The purpose of the PoliBeetle is to detect any damages caused by small space debris to the external structure.

In order to achieve its mission we designed the PoliBeetle with two radar/lidar antennas (like a real beetle), making it able to cover the surface and find eventual damages.

The PoliBeetle needed a propulsion system which could make him flying around the main ship. Designing it we met some issues to resolve:

1. Find a light engine, in order not to be relevant on the mass amount of the spaceship;
2. Find an engine which has not problem in terms of storage of fuel (avoiding big tank or chemical dangerous fuels);
3. An easy rechargeable engine to avoid the need of a extra fuel supply system.

At the end we found our ideal propulsion system fitting those problems in the Ionic Propulsion. As said before this report will show how we reached this conclusion.

1)Finding a light, little engine

Due to the fact that our flying inspector must be part of the spacecraft as an istrument for safety, we decided to avoid any tipe of engine which will take to big dimesions or heavy components.

We made this choice in order to make the PoliBeetle able to be "installed" in every spacecraft, without worrying before about its contribution to the ships dynamics.

We are thinking about the PoliBeetle as an instrument similar in dimensions and behaviour to a CubeSat, making it an easy load to be carried on board.

This was the first motivation we took to chose the Ionic Propulsion, a small and relatively light engine, already been used for CubeSats propulsion systems.

2)The storage problem

One of the problem we met was the storage of the PoliBeetle fuel: we wanted to not use propellants (fuels and oxidizers) with an high risk of dangerous behaviours in extremes situations.

We would not know how much time can pass between the mission start and the first use of the PoliBeetle, so all the issues regarding the chemical corrosion, the temperature of storage must be a problem to evitate.

Again one of the best solution found was the Ionic one because of the small quantity of gas to be ionized to store on board and the possibility to use the electrical energy produced by the sppacecraft itself.

3)The need of a long lasting engine

Coming back to the problem related to the long possible period of stay in space, away from Earth and an easy fuel supply, the PoliBeetle engine must be autonomous.

Thinking about that we choose a Ionic propulsor, because its works accelerating electrons in gasses using electrical (and/or magnetic) energy, which is easy to take from rechargeable batteries. The batteries themselves can be easy charged in a small dock linked to the capsule.

CONCLUSIONS

Making a summary of the process made for choosing the engines of the PoliBeetle, we can assume that the best fitting solution to our problem is something small, light and energy-supply free, without the needing of an high specific impulse or a very big thrust. This needings can be satisfyied well by a Ionic propulsor.

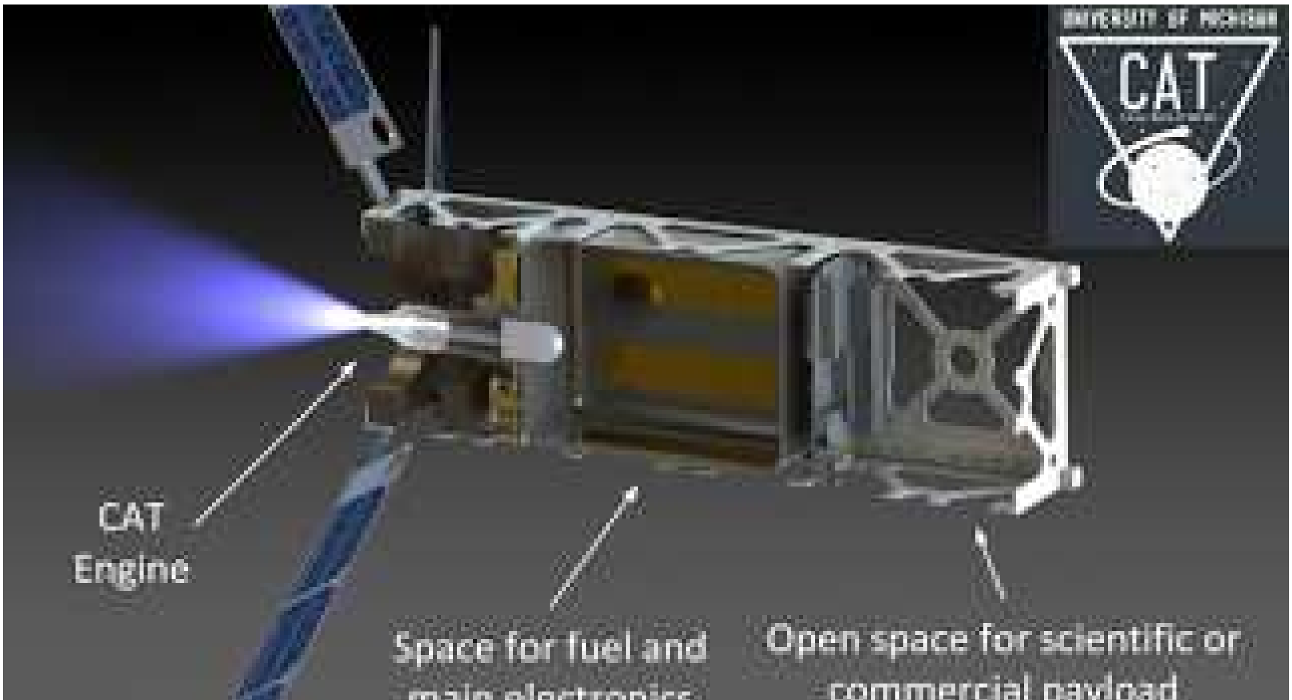
We must say that with the small amount of time we got, we hadn't the chance to make a mathematical dimensioning and comparison between a chemical engine and different types of Ionic propulsor. We took inspiration and considerations from the scientific literature and the common use of engines made for those small satellites.

You can find in the next sheets some data collected during this research work.

Appendix A1

Ion engine for CubeSat

Here you can see a picture taken from a reasearch of the Michigan University, showing an Ion engine applied to a CubeSat. You can see how small it is, around 1/3 of the CubeSat volume. According to this research this kind of engine will permit also an interplanetary mission, for example in the need of the CubeSat orbiting around Mars.



Credits: University of Michigan

For the all research:

https://www.nextbigfuture.com/2013/12/xenon-ion-and-water-cubesat-engines-for.html

Appendix B1

Stabilization and small monouvers with cold gas engines

It will be possible thata the PoliBeetle needs to orbiting around his main spacecraft to better check the damages of the surface, instead of moving from side to side with a straight line.

To better be able to do those special trajectories the main Ion engine must cooperate with other small systems of correction of the trajectory.

We identified those kind of system in small cold gas “engines”. Like the ones used in the astronaut’s backpacks during the extraveicular activities.

Those engines permit to use small ejections of gas in order to slightly correct the path of the PoliBeetle and the control of its altitude from the main spacecraft.

It is also possible to think about a system of recharging the cold gas tanks, maybe using a small system of compressed recycled air onboard the spacecraft.

More informations on:

“An Overview of Cube-Satellite Propulsion Technologies and Trends”, Akshay Reddy Tummala and Atri Dutta -Department of Aerospace Engineering, Wichita State University, PDF document

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CHAPTER 2:

DEPLOY SYSTEM AND DOCKING STATION FOR PoliBeetle-7

Abstract

In order to project the exit of the PoliBeetle from the spacecraft and its return to it, we imagined a system inspired by the deplying system of the CubeSat called P-POD.

The P-POD is a small light system (about 3-4 kg, loaded, 2kg empty) with a not large volume, easy to install, maybe near an eventually door created to permit the extravehicular activities for the astronauts.

The P-POD system, however, is designed to only deploy the CubeSats and using a spring system to push them off, but we need to have the PoliBeetle coming back to the main spacraft, docking itself to it and be alble to restart again its job.

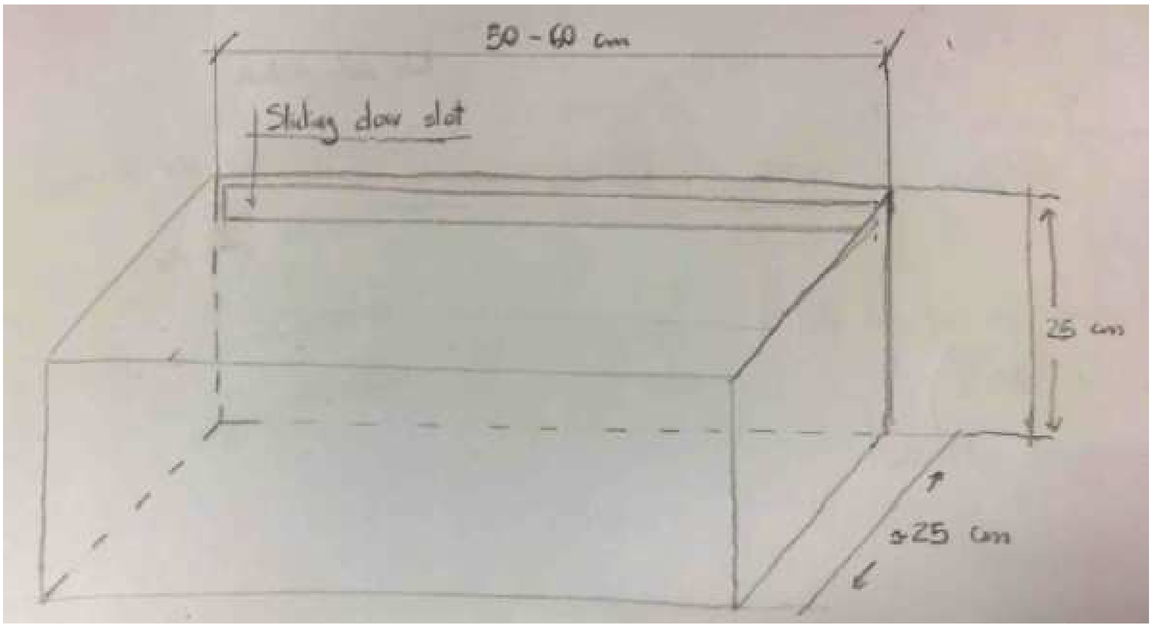
To achieve this objective we ideated a system, similar to the P-POD design, made by a parallelepiped slot “digged” in the spacecraft.

This slot is equipped with a deploying arm, similar to the one of which was equipped the space shuttle in oder to put satellites like hubble in orbit, able to push the PoliBeetle outside and made it able to start its checking flight. The arm then has got a docking system able to hook the PoliNeedle when it finishes its work and can retire into the slot. The slot has got a sliding door that can be closed to protect our inspector and a system to recharge the PoliBeetle batteries. It can be also equipped with a small “inside door” that can be open (after a pressurization of the slot closed) by the spacecraft team in order to make some eventual repairs to the flying inspector.

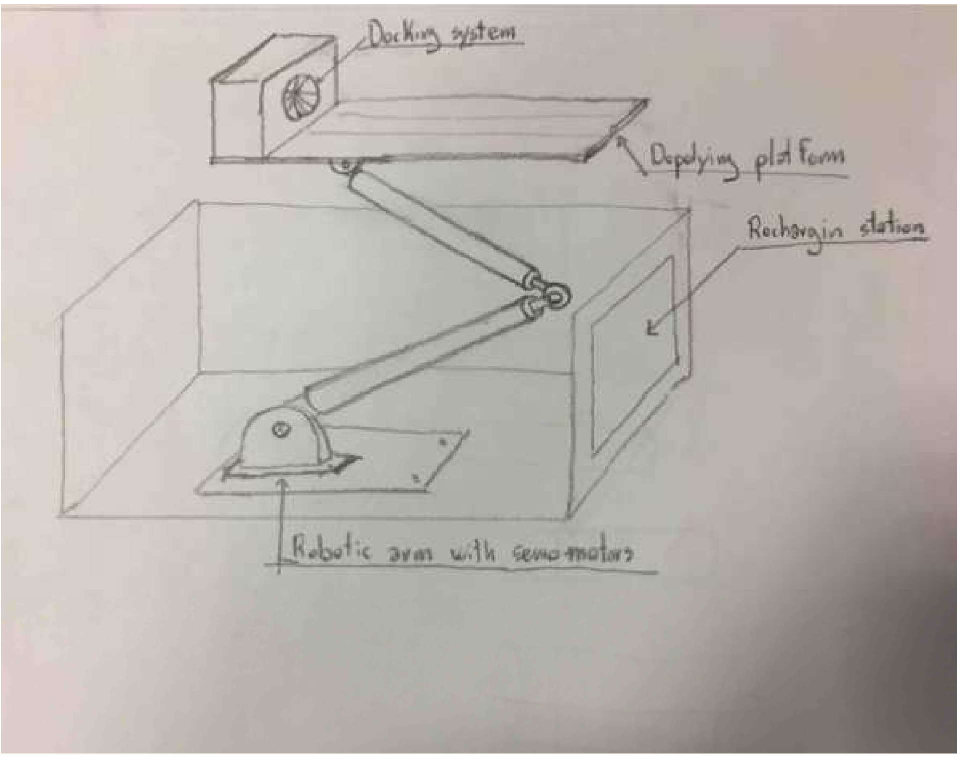
System drawings and concepts

Depending on time and because of we decided to focus better on the sensor design of PoliBeetle, we produced those drawing to express the concepts behind what was listened before.

The first drawing shows the parallelepiped slot and the dimensions we estimated to let the PoliBeetle be closed inside. You can also spot the slot made for the sliding door.



After the dimensioning of the slot we proceeded with the ideal design of the things inside it.



Above you can see the drawing about the robotic arm inspired by the Space Shuttle one, a docking system inspired by the one used between the International Space Station and the Soyuz spacecraft, a platform where to lock the PoliBeetle while it is in dock mode and a wall equipped with sliding sticks that can reach the PoliBeetle while docked and recharge its batteries.

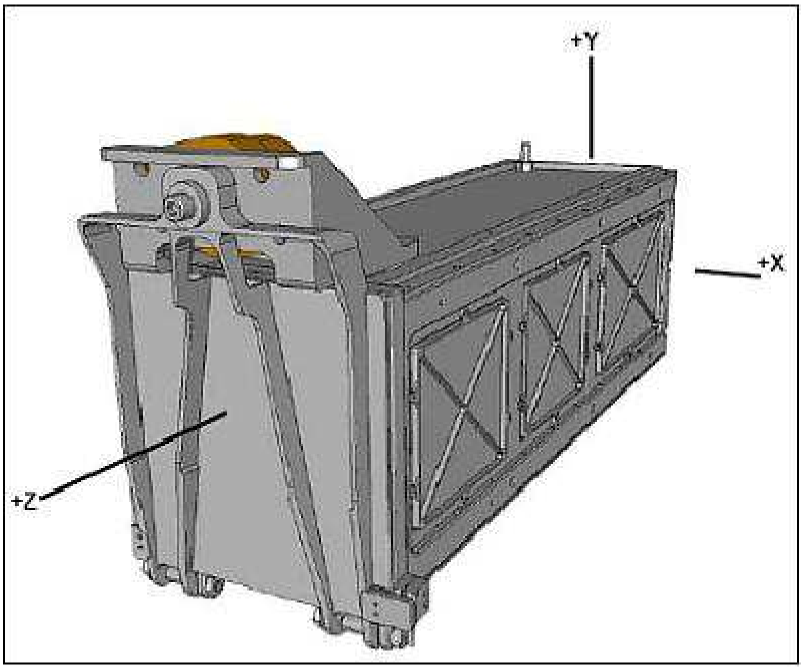
Appendix A2

System from wich we took inspiration

As sad above we took inspiration for the deploying system and the docking system from the NASA robotic arm of which were equipped the Space Shuttles.

A pic of the robotic arm of the shuttle, called “Canadarm”, while working . *Credits: Wikipedia*

We also took inspiration from the P-POD deploying system of cubesats, that helped us designing the slot for PoliBeetle.



3D model of a P-POD deploying system. *Credits: eoPortal*

A concrete P-POD launch system. *Credits: Amstad UK*

Other information we took about the P-POD system can be found at:

*"CubeSat development workshop",*CAL Poly, Powerpoint presentation

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CHAPTER 3:

DEPLOY SYSTEM AND DOCKING STATION FOR

PoliBeetle-7

The free-flyer PoliBeetle-7 will use sensors based on visual / electromagnetic waves to inspect the spacecraft for damage. It is not possible to use other waves (for instance: sound) since they are mechanical waves which need a spread medium.

In this part of the project two different technologies are discussed: RADAR and LIDAR.
The first one is presented in detail, paying particularly attention to the imaging and data processing.
The second one and the reason why the LIDAR technology fits better the mission goal are then shortly explained, since the imaging and data processing is very similar to the first.

RADAR TECHNOLOGY

Radar is an object-detection system that uses radio waves to determine the range, angle, or velocity of objects. It can be used to detect aircraft, ships, spacecraft, guided missiles, motor vehicles, weather formations, and terrain. A radar system consists of a transmitter producing electromagnetic waves in the radio or microwaves domain, a transmitting antenna, a receiving antenna (often the same antenna is used for transmitting and receiving) and a receiver and processor to determine properties of the objects. Radio waves (pulsed or continuous) from the transmitter reflect off the object and return to the receiver, giving information about the object's location and speed. [1]

In order to describe how the radar processing works, a realistic example is considered: the RADAR is used to detect an aircraft 150 km distant. The aim of this dissertation is to illustrate the main principles of signal processing and the reasons why a RADAR does not fit the mission requirements.

Hence, a RADAR system that operates with a central frequency of $f_0 = 3 \text{ GHz}$ (Band S RADAR, typical frequency band for detecting aircrafts) is considered. It is characterized with an angular sector 2° wide in azimuth and 20° wide in elevation. The system must be able to detect the object and evaluate its position, within a distance of 150 km. Thus:

$$\Delta\psi = 2° = \frac{\pi}{90} \cong 0.035 \qquad \Delta\theta = 20° = \frac{\pi}{9} \cong 0.35 \qquad R_{max} = 150 \text{ km} = 150 \cdot 10^3 \text{ m}$$

The wavelength is:

$$\lambda = \frac{c}{f_0} \cong 0.1 \text{ m} = 10 \text{ cm}$$

where c is the speed of light, approximated with the value of $c \cong 3 \cdot 10^8 \text{ m/s}$.

In order to evaluate the required antenna size, some assumptions are made to simplify the dissertation: the temporal variation of the signal sources are supposed proportional to the signal applied to the antenna and

the spatial distribution of the sources along the antenna is uniform.
In addition to this, the antenna is considered plane and rectangular.

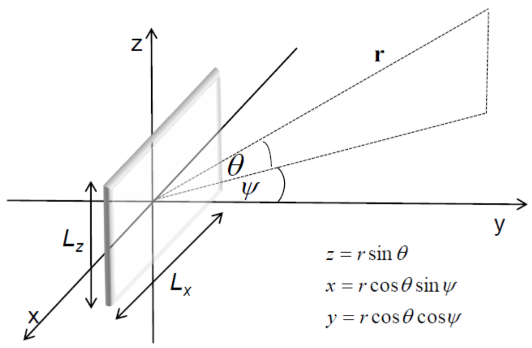


Figure 1. *Plane rectangular antenna representation*

Thus, thanks to the simplified antenna model, the rectangular antenna has in azimuth a width equal to:

$$L_x = \frac{\lambda}{\Delta\psi} \cong 2.865 \text{ m}$$

and an elevation width equal to:

$$L_z = \frac{\lambda}{\Delta\theta} \cong 0.2865 \text{ m}$$

from which we can evaluate the area:

$$A = L_x L_z \cong 0.821 \text{ m}^2$$

Now it is possible to calculate the gain of the antenna. The gain is defined as a parameter that quantifies the portion of power that is irradiated towards the maximum, that is, for a plane rectangular antenna, in the direction of its central axis $y \Leftrightarrow \theta = 0$ and $\psi = 0$.

Thus, if we consider the definition of gain, it becomes:

$$G = \frac{4\pi}{\oint f(\theta,\psi)\, \mathrm{d}\Omega}$$

that is the ratio of the spherical surface (represented by the 4π steradians) on the directivity function weighted on each $\mathrm{d}\Omega$ steradiant. Considering the simplifying assumption that for a plane rectangular antenna the transmitted power is uniformly distributed in the solid angle described by $\Delta\psi$ and $\Delta\theta$ (and zero everywhere else) it can be demonstrated that:

$$\oint f(\theta,\psi)\, \mathrm{d}\Omega \cong \Delta\Omega \cong \Delta\theta \cdot \Delta\psi = \frac{\pi^2}{810} \cong 0.0122$$

It could also be written as:

$$\oint f(\theta,\psi)\, \mathrm{d}\Omega \cong \Delta\Omega \cong \Delta\theta \cdot \Delta\psi = \frac{\lambda}{L_x} \cdot \frac{\lambda}{L_z} = \frac{\lambda^2}{A_{antenna}}$$

allowing to demonstrate the most common used formula for a plane rectangular antenna:

$$G = \frac{4\pi}{\lambda^2} A_{antenna}$$

that, with an efficiency η (here considered equal to 0.5), which takes into account every possible loss, becomes:

$$G = \frac{4\pi}{\lambda^2} \eta A_{antenna} = \frac{3'240}{\pi} \eta = \frac{1'620}{\pi} \cong 515.662$$

It is possible to observe a very high gain ($G \gg 1$) which describes a very good focalization of the antenna. These results were predictable as the “visive cone” of the RADAR is very narrow, characterised by only 2° in azimuth and 20° in elevation.

The power received by the RADAR must be evaluated. Obviously, the power hitting the aircraft is not reflected equally in the RADAR direction. In order to estimate how much power is reflected towards the RADAR the *Radar Cross Section* (*RCS*) is used as it takes into account both the scattering (backscatter coefficient) and the area illuminated by the RADAR.

The aircraft is supposed not to use any *stealth* technology, so it can be considered [2][3]

$$RCS = 50$$

for S band signals.

For plane rectangular antennas, the directivity function can be approximated as:

$$f(\theta) \cong \mathrm{sinc}^2\left(\frac{\theta}{\Delta\theta}\right)$$

If the aircraft is in the direction of the RADAR central axis ($\theta = 0$, where the directivity function assumes the maximum value equal to 1) and the RADAR transmits a unitary power $P_{tx} = 1$ W, by using the *Radar Equation*, it is possible to calculate the power received after the reflection from an aircraft which position is $R = 150$ km far from the RADAR and with an $RCS = 50$:

$$P_{rx} = \frac{P_{tx}}{(4\pi R^2)^2} G A_{antenna} \cdot f^2(0) \cdot RCS \cong 2.647 \cdot 10^{-19} \text{ W} \cong -185.8 \text{ dB}$$

In Figure 2 the received power is represented in decibels as a function of the distance:

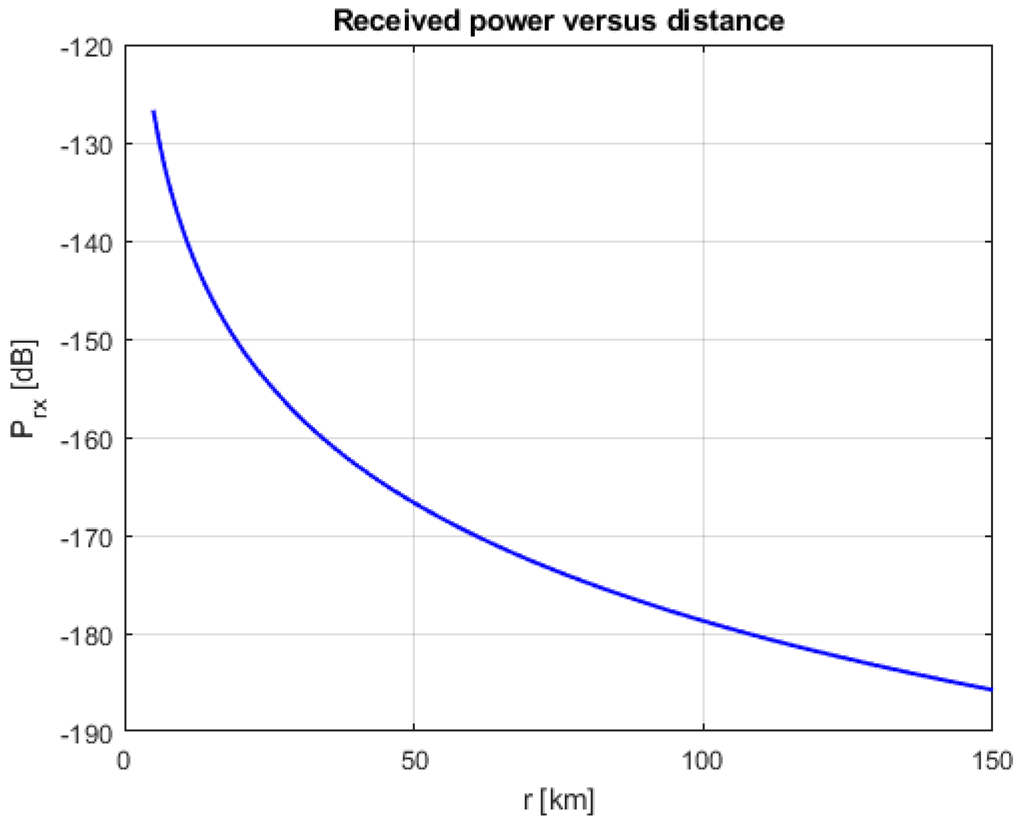


Figure 2. *Received power by the RADAR versus the distance of the aircraft*

Thus, since the RADAR wants to detect an object within $150\ \mathrm{km}$ (with an $RCS = 50$) by transmitting only $1\ \mathrm{W}$ of power, it should be sensible to a received power equal to $-185.8\ \mathrm{dB}$. Obviously, the received power is too small to be detected by a RADAR and, in fact, the detecting aircraft RADARs do not transmit a power equal to $1\ \mathrm{W}$: they can actually transmit a power equal to some megawatts (MW). However, a unitary power was supposed, since, whatever the RADAR power is, it is possible to multiply the following results for the real transmitted power in order to obtain the correct results.
In particular, the power will be later modified when the *Signal to Noise Ratio* (SNR) will be introduced.

The frequency band width is determined by the constraints of the resolution in range and by the assumptions made which imply a frequency band width much smaller than the central frequency. [4]

In fact, in order to make two different objects distinguishable for a RADAR, their relative distance must be greater than:

$$\rho_r = \frac{c}{2B}$$

where B is the frequency band width, in order to avoid the signals overlap. Thus, for a range resolution of about one meter a frequency band width equal to $B = 100\ \mathrm{MHz}$ must be chosen. In fact, with that band width, the resolution in range would be $\rho_r = 1.5\ \mathrm{m}$. Anyway, a band width large B, implies a sampling time Δt equal to:

$$\Delta t < \frac{1}{B} = 1 \cdot 10^{-8}\ \mathrm{s}$$

to obtain a correct sampling (without aliasing). However, a small sampling time implies a longer data processing which returns less precise results, as the aircraft may move radially with a velocity equal to $20\ \mathrm{m/s}$ after $1\ \mathrm{s}$ of data processing the aircraft goes $20\ \mathrm{m}$ away.

Furthermore, in order to use the simplified dissertation, it must be $B \ll f_0$ and by evaluating the ratio B/f_0 with $B = 100\ \mathrm{MHz}$ it is $B/f_0 \cong 0.033$ which is small, but surely greater than the ratio with $B = 10\ \mathrm{MHz}$ $\Rightarrow\ B/f_0 \cong 0.0033$.

As the considered RADAR is a pulse RADAR and not a continuous-wave RADAR (*FMCW*) the impulse duration is surely much smaller than the temporal distance between two different pulses, often referred to as *PRI* (*Pulse Repetition Interval*).

Considering that the maximum range of the RADAR is $150\ \mathrm{km}$, a minimum temporal distance equal to PRI_{min} between two pulses must be guaranteed:

$$PRI_{min} = \frac{2R_{max}}{c} = 0.001\ \mathrm{s}$$

since, if the temporal distance between two consecutive pulses had been smaller, the reflected pulses would have occurred in the next "temporal window" obstructing the possibility to identify the transmitted pulse (Figure 3).

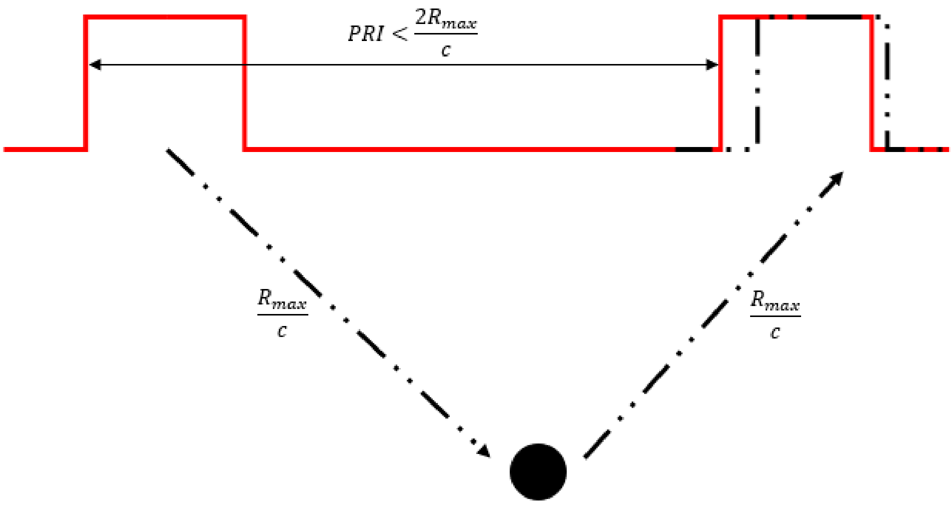


Figure 3. *What would happen if the pulses were distant in time less than PRI$_{min}$*

Thus a $PRI = 3PRI_{min} = 0.003$ s is chosen with a scaling factor equal to 3 (a scaling factor greater than 2 is chosen as, considering all the "temporal windows" symmetric about 0, with a scaling factor equal to 2 the maximum distance would fall exactly at the beginning/end of the "temporal windows" with the consequent overlap).

Thus, as it was stated before, the signal is impulsive and its duration (referred to as T_{oss}) must be a very small fraction of the PRI_{min}. A fraction equal to the 3% of the PRI_{min} is chosen, so the pulse duration is:

$$T_{oss} = \frac{3PRI_{min}}{100} = 30 \cdot 10^{-6}\ \mathrm{s} = 30\ \mu\mathrm{s}$$

With this duration, the RADAR is not able to detect objects located in a space range included within R_{min}: that is the limit distance for which, while the RADAR is transmitting, it already receives the initial part of the pulse that is transmitting (Figure 4).

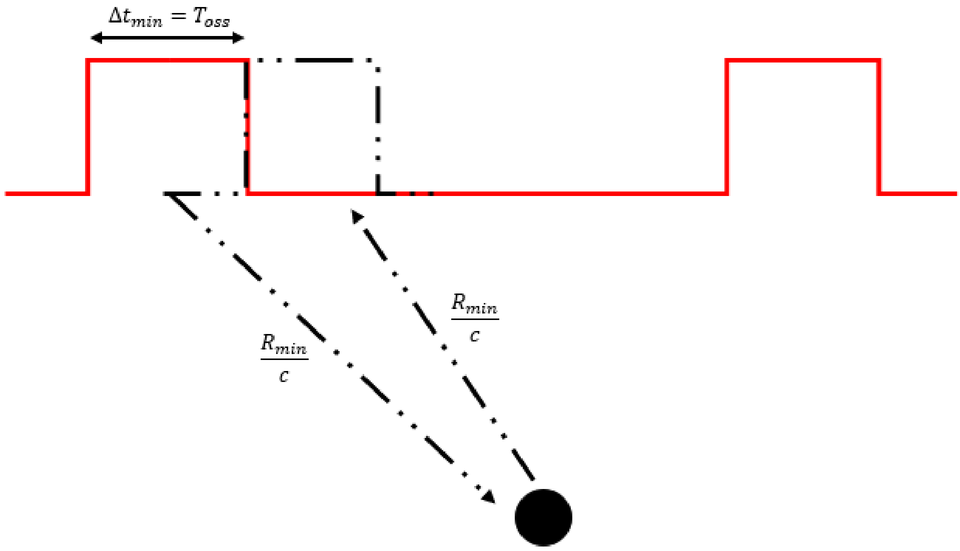


Figure 4. *Minimum distance from which the RADAR is capable to detect an object*

This distance is equal to:

$$\frac{R_{min}}{c} + \frac{R_{min}}{c} = \frac{2R_{min}}{c} = \Delta t_{min} = T_{oss} \Rightarrow R_{min} = \frac{c \cdot T_{oss}}{2} = 4.5 \text{ km}$$

Hence, the RADAR can detect objects located in the range of $(4.5 \text{ km}, 150 \text{ km})$.

Furthermore, the velocity resolution (which will be used to evaluate the radial velocity of the aircraft) is:

$$\rho_v = \frac{c}{2f_0 T_{oss}} \cong 166.67 \text{ m/s}$$

Eventually, a band width of $B = 10 \text{ MHz}$ and a pulse duration of $T_{oss} = 30$ µs are chosen.

The chosen analytic equation of the pulse is an up-chirp:

$$g(t) = \text{rect}\left(\frac{t}{T_{oss}}\right) \cdot e^{i\pi\alpha t^2} \qquad \text{with} \qquad \alpha = \frac{B}{T_{oss}}$$

The choice of this kind of signal is suggested by the advantage of using a phase proportional to the duration of the pulse: it is possible to illuminate the object for a longer time using a smaller amount of power.

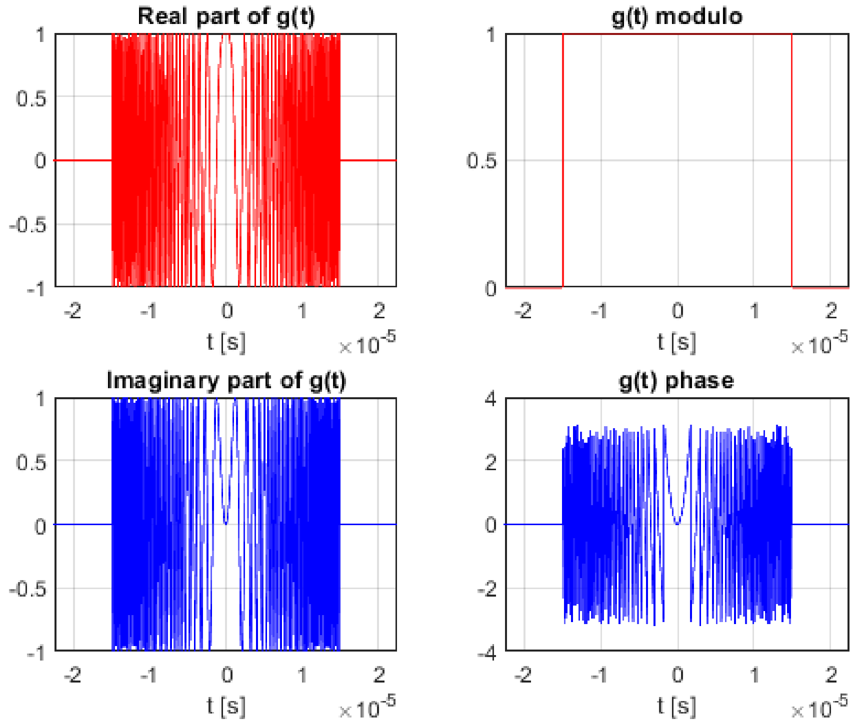


Figure 5. *Pulse (up-chirp) in the time domain*

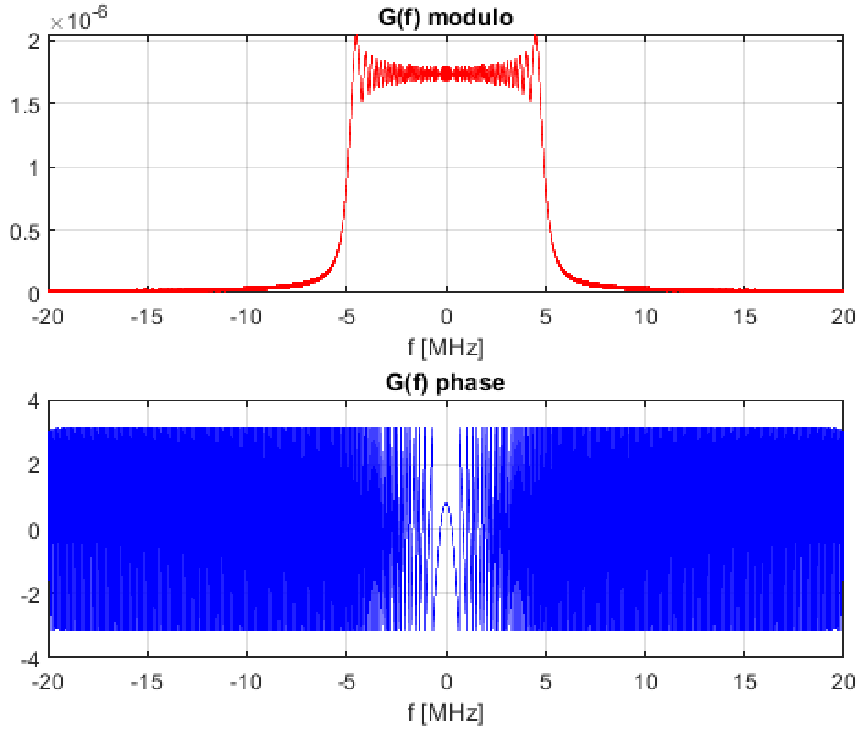


Figure 6. *Pulse (up-chirp) in the frequency domain*

A noise with a power spectral density equal to $N_0 = KT_0F$ is considered, where $K = 1.38 \cdot 10^{-23}$ J/K is the Boltzmann constant, $T_0 = 290$ K the reference temperature for the thermic noise and $F = 3$ is the figure of noise. Thus, the power spectral density is:

$$N_0 = KT_0F = 1.2006 \cdot 10^{-20}\ \mathrm{J}$$

and its power (in the RADAR frequency band) is:

$$P_n = N_0 \cdot B = 1.2006 \cdot 10^{-13}\ \mathrm{W}$$

The power of the RADAR transmitted signal is such that the minimum *Signal to Noise Ratio (SNR)* is at least equal to $10\ \mathrm{dB} = 10$. It has already been demonstrated in [4] that:

$$SNR = \frac{P_{rx} \cdot T_{ill}}{N_0} = \frac{P_{rx} \cdot T_{oss}}{N_0}$$

and it is possible to calculate the minimum power received by the RADAR and it is:

$$P_{rx} = \frac{SNR \cdot N_0}{T_{oss}} = 4.002 \cdot 10^{-15}\ \mathrm{W}$$

To receive that amount of power the RADAR must transmit (according to the *Radar Equation*) a power equal to:

$$P_{tx} = \frac{P_{rx} \cdot (4\pi R_{ax}^2)^2}{G \cdot RCS \cdot A_{antenna} \cdot f^2(\Delta\theta/2)} \cong 92'050\ \mathrm{W}$$

where it is considered $\theta = \frac{\Delta\theta}{2}$ in order to have a signal/noise ratio always greater than 10 even when the object just entered the “visive cone” of the RADAR which is also the minimum received power condition.

A transmitted power equal to $P_{tx} = 100\ \mathrm{kW}$ is chosen. Thus, if an aircraft ($RCS\ =\ 50$) is located on the RADAR axis ($\theta = 0$) $150\ \mathrm{km}$ away, the power received by the RADAR is $100'000$ times the received power calculated at the beginning:

$$P_{rx} = 100'000 \cdot 2.647 \cdot 10^{-19}\ \mathrm{W} = 2.647 \cdot 10^{-14}\ \mathrm{W} = -135.8\ \mathrm{dB}$$

The RADAR system, in order to detect an object $150\ \mathrm{km}$ away, must have a sensor sensible to at least $-135.8\ \mathrm{dB}$.

In particular, if an up-chirp pulse is transmitted, the same object (<u>without noise and with a radial speed equal to zero</u>) would reflect the signal which, after the adapted filter, becomes (Figure 7):

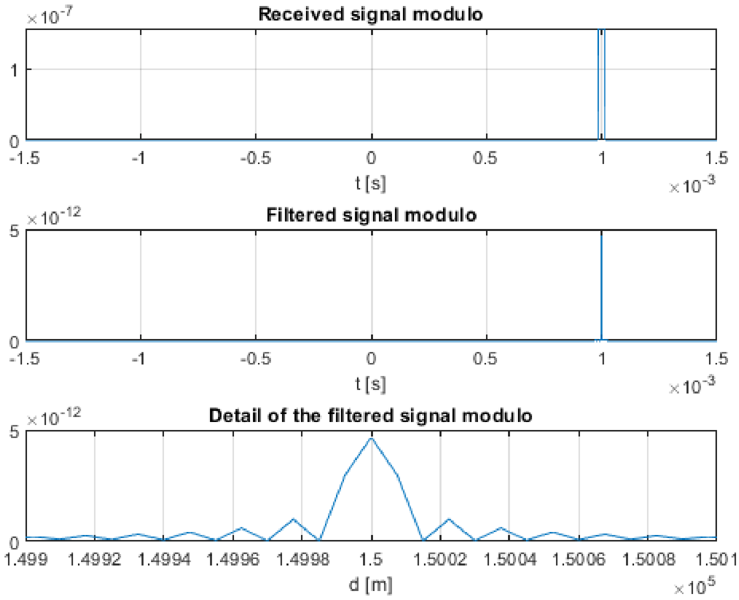


***Figure 7.** Reflected pulse with a band width of 10 MHz and a sampling scaling coefficient of 2*

where a sampling time of $\Delta t = \frac{1}{2B}$ was chosen obtaining the result in 1.18 seconds. The peak is obtained exactly in $R = 150 \text{ km}$, as expected.
The central lobe is $2\rho_r = 30 \text{ m}$ wide.

If a frequency band width of $B = 100 \text{ MHz}$ had been chosen, as suggested before, with a sampling time of $\Delta t = \frac{1}{4B}$, the following plot would have been obtained:

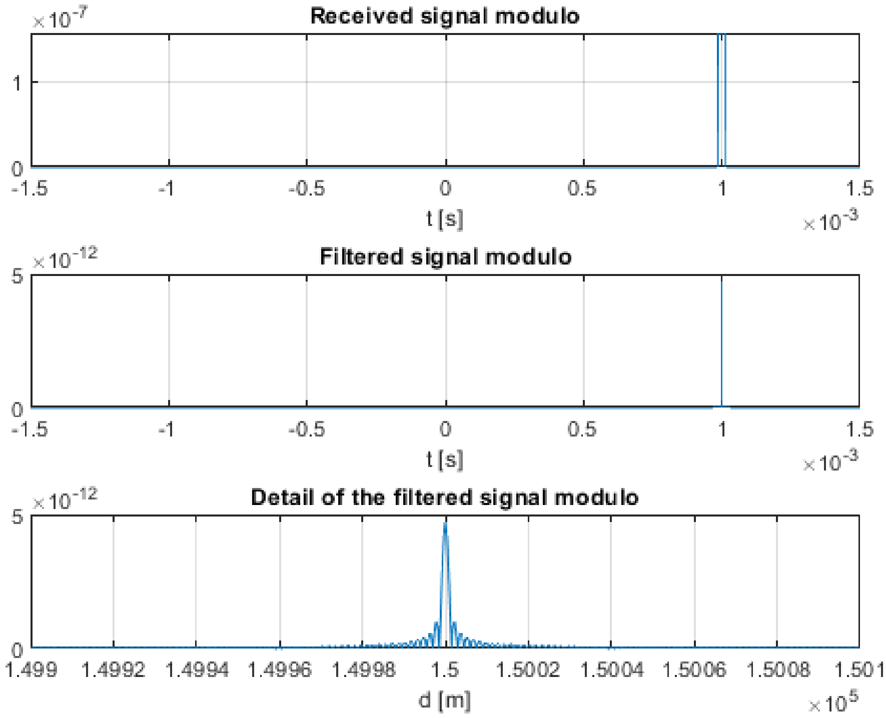


__Figure 8.__ Reflected pulse with a band width of 100 MHz and a sampling scaling coefficient of 4

with an elapsed time equal to 21.2 seconds.
The central lobe is much narrower (now equal to $2\rho_r = 3\ \mathrm{m}$) and the curve is smoother (because of the smaller sampling time) but the elapsing time is much greater (18 times greater than the previous).

Thus, $B = 10\ \mathrm{MHz}$ and $\Delta t = \frac{1}{2B}$ are still chosen, since the results are considered satisfying.

If the noise is taken into account, the plot of the filtered signal becomes:

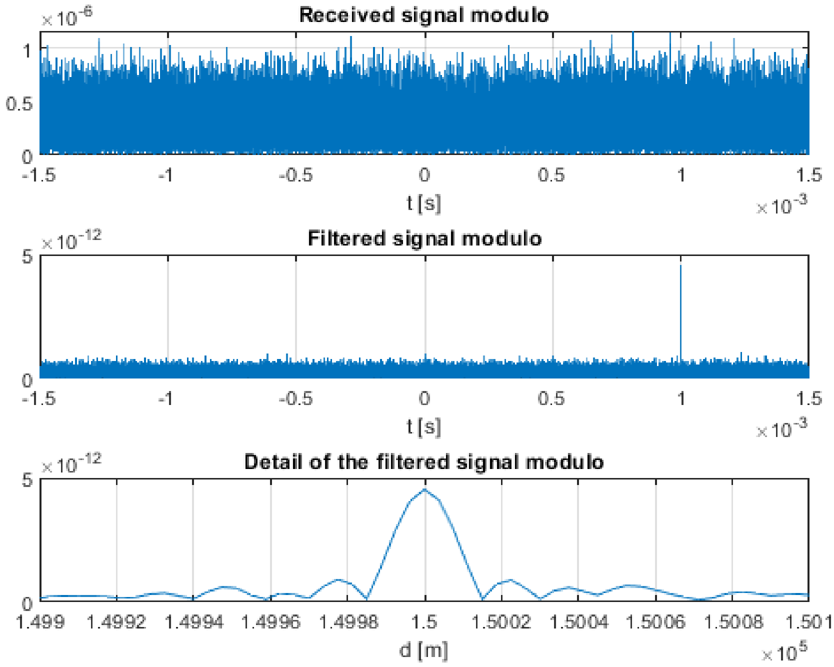


Figure 9. *Detecting an aircraft 150 km away with an up-chirp (B = 10 MHz and t = 1/2B) with noise*

It is clear that, before filtering the signal, it was impossible to distinguish the power peak from the power peaks of the noise. However, after filtering the signal, it was immediately possible to distinguish the power peak corresponding to the object located at $150\ \mathrm{km}$. This was possible because the following condition was imposed: $SNR \geq 10\ \mathrm{dB}$.

Until now, we transmitted a signal equal to:

$$s_{tx} = \sqrt{P_{tx}}g(t)e^{i2\pi f_0 t}$$

where $g(t)$ was the up-chirp. Thus, after the reflection, we had a signal like:

$$s_{rx} = \sqrt{P_{rx}}g\left(t - \frac{2R}{c}\right)e^{i2\pi f_0\left(t-\frac{2R}{c}\right)}$$

which was firstly demodulated (brought again in the base band):

$$s_{rx}^{dem} = s_{rx} \cdot e^{-i2\pi f_0 t} = \sqrt{P_{rx}}g\left(t - \frac{2R}{c}\right)e^{-i4\pi\frac{f_0}{c}R}$$

and, afterwards, filtered with an adapted filter $h(t) = g^*(-t)$ which guarantees the maximum SNR ratio, [4] obtaining a final signal with the following analytic expression:

$$s_{rx}^{fil} = s_{rx}^{dem} * h(t)$$

In order to find the distance of the object, the delay of the pulse (demodulated and filtrated) was firstly observed and then it was converted into a distance: $\tau = \frac{2R}{c}$.

However, if the aircraft is moving with a radial speed equal to v_r the Doppler effect occurs and it allows to find the velocity. In fact, the demodulated signal is now actually:

$$s_{rx}^{dem} = \sqrt{P_{rx}} g\left(t - \frac{2R(t)}{c}\right) e^{-i4\pi\frac{f_0}{c}R(t)}$$

with the difference that the distance of the object, now, depends on time. It is possible to write $R(t) \cong R_0 + v_r t$ obtaining what follows:

$$s_{rx}^{dem} = \sqrt{P_{rx}} g\left(t\left(1 - \frac{2v_r}{c}\right) - \frac{2R_0}{c}\right) e^{-i4\pi\frac{f_0}{c}R_0} e^{-i4\pi\frac{f_0}{c}v_r t}$$

Using the following approximation: $1 - \frac{2v_r}{c} \cong 1$ the filter is characterised by the following expression:

$$s_{rx}^{dem} = \sqrt{P_{rx}} g\left(t - \frac{2R_0}{c}\right) e^{-i4\pi\frac{f_0}{c}R_0} e^{-i2\pi\frac{2f_0v_r}{c}t}$$

where the Doppler frequency is defined as:

$$f_d = \frac{2f_0v_r}{c}$$

Thus, to filter properly, the Doppler frequency should be known in advance in order to properly define the filter. Now a frequency shift occurs: if the signal was filtered immediately without considering the f_d value a big part of the pulse would be lost.
So an array of Doppler frequencies are taken into account and the demodulated signal is multiplied with all the Doppler frequencies in the array (in order to cancel the frequency shift) and then it is filtered with the filter corresponding to each frequency: for the scalar product properties the "function" will assume its maximum value when the filter assumes the exact Doppler frequency (v_r) and in correspondence to the exact delay (R_0).

The matrix would assume this form:

$$\begin{array}{l|l}
f_d\ (\mathrm{1} & s_{rx}^{dem} \cdot e^{i2\pi f_{d_1}t} * g^*(-t) \\
 & s_{rx}^{dem} \cdot e^{i2\pi f_{d_2}t} * g^*(-t) \\
 & \ldots \\
 & s_{rx}^{dem} \cdot e^{i2\pi f_{d_n}t} * g^*(-t) \\
\hline
 & \qquad\qquad\qquad \tau\ (R_0)
\end{array}$$

In order to build the Doppler frequencies array, consider its definition: $f_d = \frac{2f_0v_r}{c}$. Thus, if the maximum velocity that the object can reach is known, it is possible to choose an array with the following range:

$$f_d \in \left(-\frac{2f_0v_{max}}{c}, +\frac{2f_0v_{max}}{c}\right)$$

with a maximum frequency resolution equal to:

$$\Delta f_d < \frac{1}{T_{oss}}$$

(it is often used $\Delta f_d = \frac{1}{4T_{oss}}$ or $\Delta f_d = \frac{1}{8T_{oss}}$).

An aircraft is supposed to be 150 km away from the RADAR, moving with a radial velocity of $v_r = 100$ m/s. If the RADAR transmitted an up-chirp, as the one defined before, and it was immediately filtered (without considering the frequency shift caused by the Doppler effect) the result would be the following:

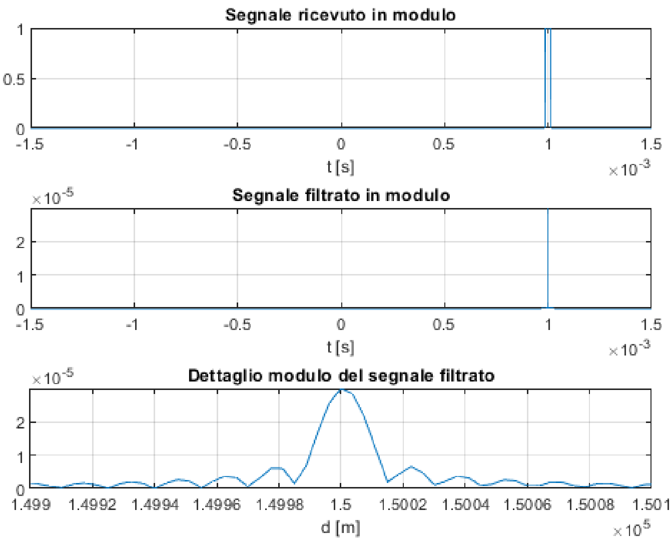


Figure 10. *Evaluation of the distance without considering the radial velocity (B = 10 MHz, t = 1/4B)*

It is possible to notice that, unlikely from Figure 7, the filtered signal in Figure 9 is slightly shifted towards the right-hand side, because the Fourier transform of the pulse is shifted in the frequency domain about a quantity equal to f_d and, so, when it multiplies the Fourier transform of the pulse, the phases are summed, but they do not cancel each other: there is consequently another delay in the time domain (beside the real delay of $\frac{2R}{c}$).

If the frequency shift is considered and the path presented until now is followed, the results below are obtained for an up-chirp:

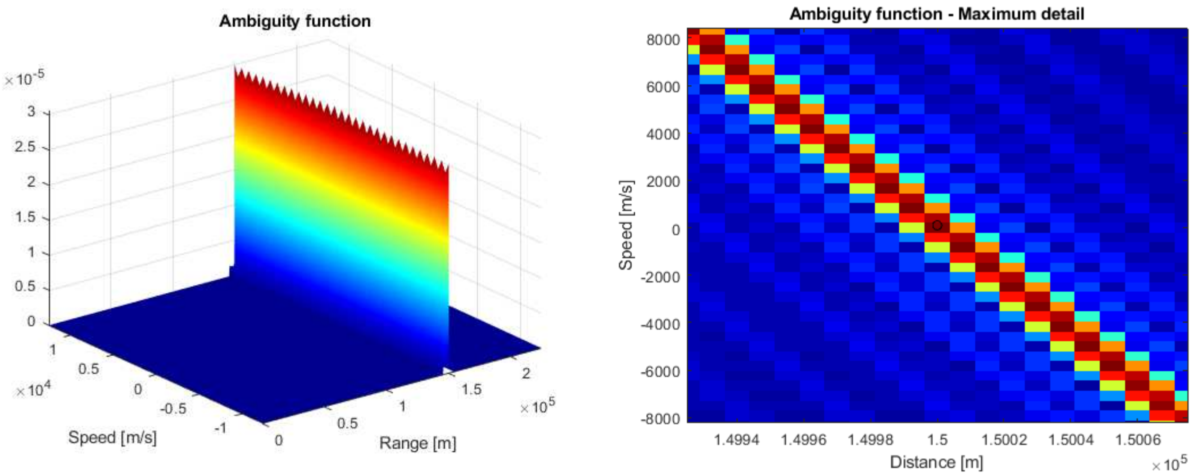


Figura 1. *Funzione di ambiguità di un up-chirp e suo dettaglio*

which means that there is not only one peak but a stripe of peaks slightly sloped that does not allow an unambiguous identification of the power peak.

In order to bypass this problem, it is possible to transmit a signal obtained as the sum of an up-chirp and the corresponding down-chirp, obtaining this result:

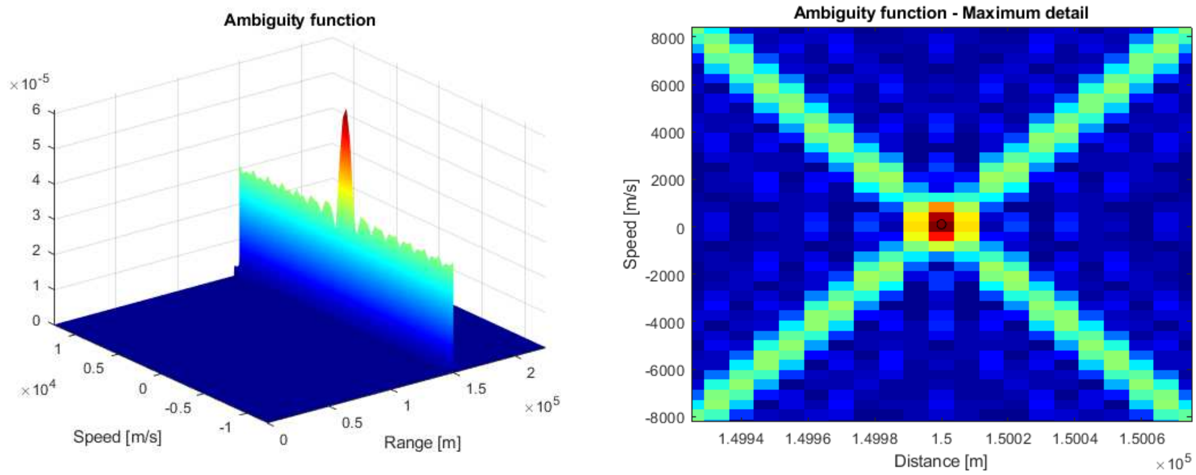


Figura 2. *Funzione di ambiguità di un up-chirp più down-chirp e suo dettaglio*

localizing perfectly the distance and the velocity (except for the resolution in range and in velocity).

It is clear that the RADAR cannot properly identify small objects since the resolution in range strongly depends on the band width. To have a resolution in range of 1 cm the band width should be $B = \frac{c}{2 \cdot \rho_r} = 1.5 \cdot 10^{10} \text{ Hz} = 15 \text{ GHz}$ which implies a maximum sampling time equal to $\Delta t = \frac{1}{B} = 0.67 \cdot 10^{-10}$. Both the band width and the sampling time are not suitable for the mission goal.

That is why LIDAR technology is the most appropriate.

LIDAR TECHNOLOGY

Before introducing the LIDAR, the definition and properties of a laser are listed.

A laser is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation.

A laser differs from other sources of light in that it emits light *coherently*, spatially and temporally. Spatial coherence allows a laser to be focused to a tight spot, enabling applications such as laser cutting and lithography. Spatial coherence also allows a laser beam to stay narrow over great distances (collimation), enabling applications such as laser pointers. Lasers can also have high temporal coherence, which allows them to emit light with a very narrow spectrum, i.e., they can emit a single colour of light. Temporal coherence can be used to produce pulses of light as short as a femtosecond. [5]

A laser rangefinder is a rangefinder that uses a laser beam to determine the distance to an object. The most common form of laser rangefinder operates on the time of flight principle by sending a laser pulse in a narrow beam towards the object and measuring the time taken by the pulse to be reflected off the target and returned to the sender. Due to the high speed of light, this technique is not appropriate for high precision sub-millimetre measurements, where triangulation and other techniques are often used. [6]

Lidar (also called LIDAR, LiDAR, and LADAR) is a surveying method that measures distance to a target by illuminating the target with pulsed laser light and measuring the reflected pulses with a sensor. Differences in laser return times and wavelengths can then be used to make digital 3-D representations of the target. The name *lidar*, now used as an acronym of *light detection and ranging* (sometimes *light imaging, detection, and ranging*), was originally a portmanteau of *light* and *radar*. Lidar sometimes is called 3D laser scanning, a special combination of a 3D scanning and laser scanning. It has terrestrial, airborne, and mobile applications. [7]

LIDAR Sensors tend to cost more than RADAR sensors for several reasons: [8]

1. LIDAR using the Time of Flight technique needs high speed electronics that cost more
2. LIDAR sensors need CCD receivers, optics, motors, and lasers to generate and receive the waves used. RADAR only needs some stationary antennas.
3. LIDAR sensors have spinning parts for scanning. That requires motors and encoders. RADAR only needs some stationary antennas.

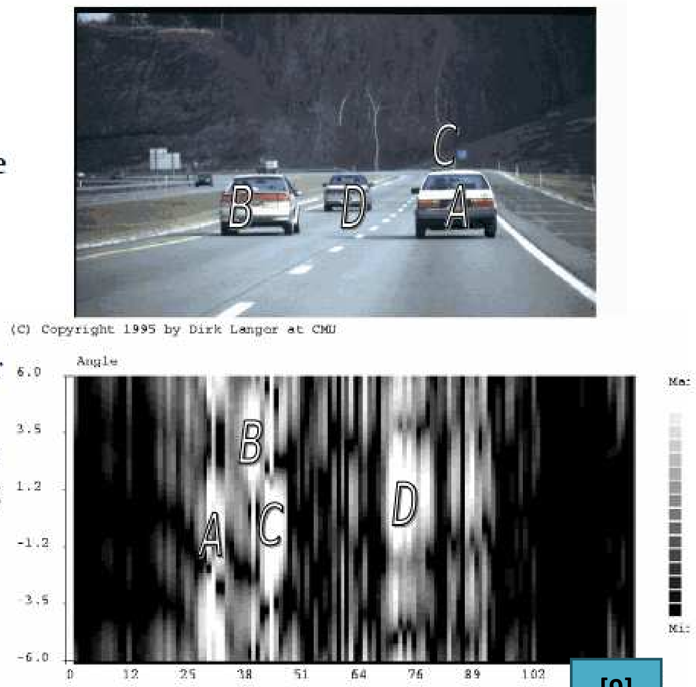
The signal processing is done in a similar way for the LIDAR as it was done for the RADAR. The key factor is the “translation” of the delay in terms of distance.
But a LIDAR, as it uses shorter wavelengths, allows the detection of small objects whereas a RADAR, as it uses longer wavelengths, does not allow the detection of small objects.

Eventually, the only technology useful to achieve the mission goal is to use a LIDAR.

The images below illustrate the power of a LIDAR.

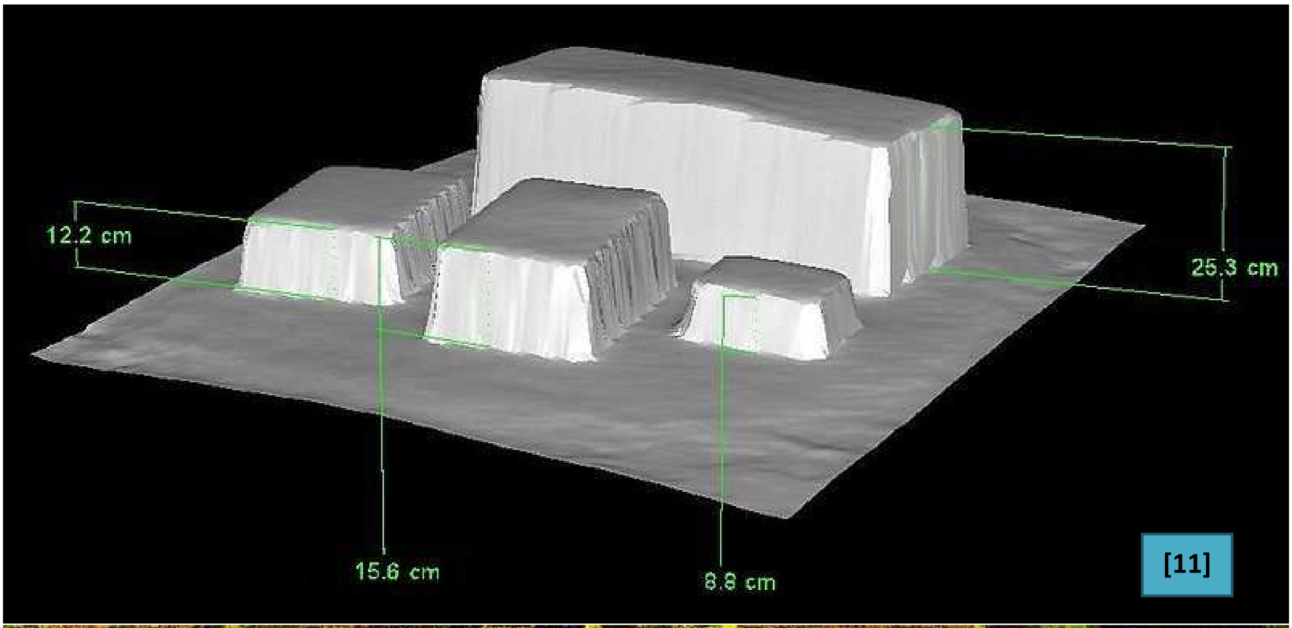
Radar Data

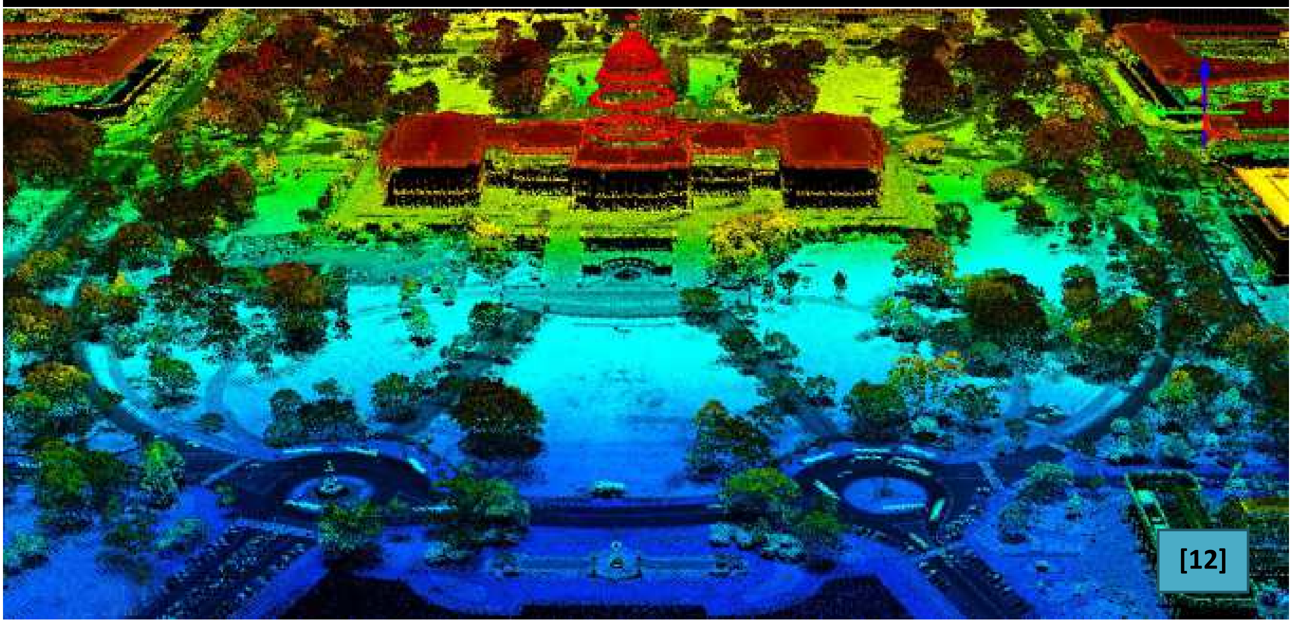
Data from a scanning radar. Top image is video of the scene, bottom is radar data, with corresponding locations marked. The radar data is range (horizontal) and bearing angle (vertical; up is left, down is right). Brightness indicates strength of return. Car A is close and he center of the radar return (the video image does not extend as far to the right as the radar); B is further and left; C is further yet and is barely visible above the roof of A; D is much further and has a bearing between A and B.

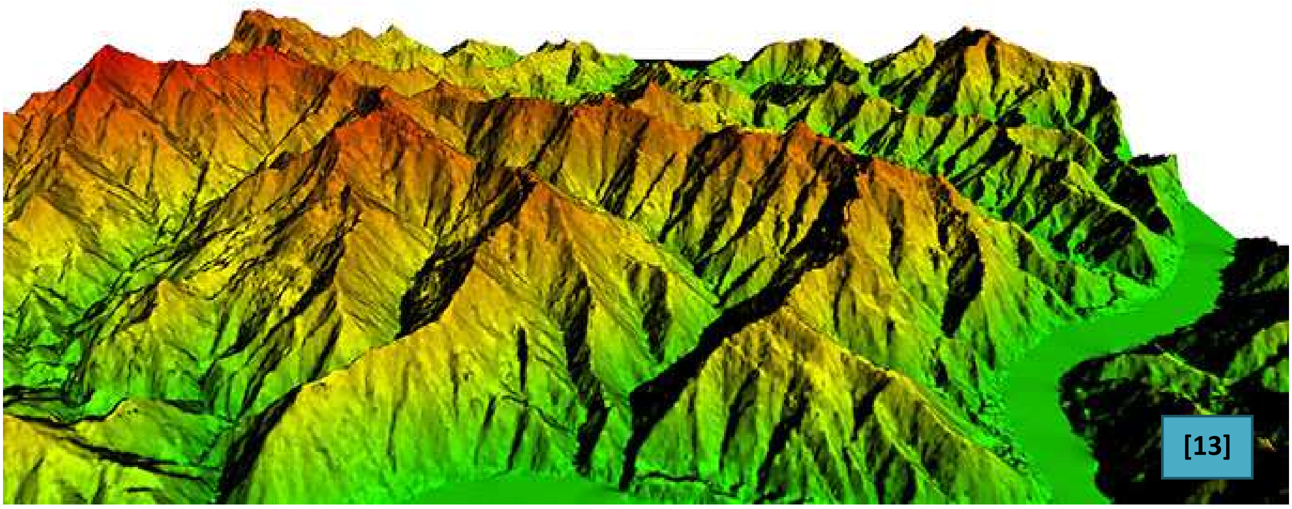


[9]


[10]


12.2 cm
25.3 cm
15.6 cm
8.8 cm
[11]


[12]


[13]

NASA Space App Challenge 2018

Challenge: **Design by Nature**

CHAPTER 4:

IMAGING SYSTEM OF THE DATA RECORDED BY

PoliBeetle-7

Abstract

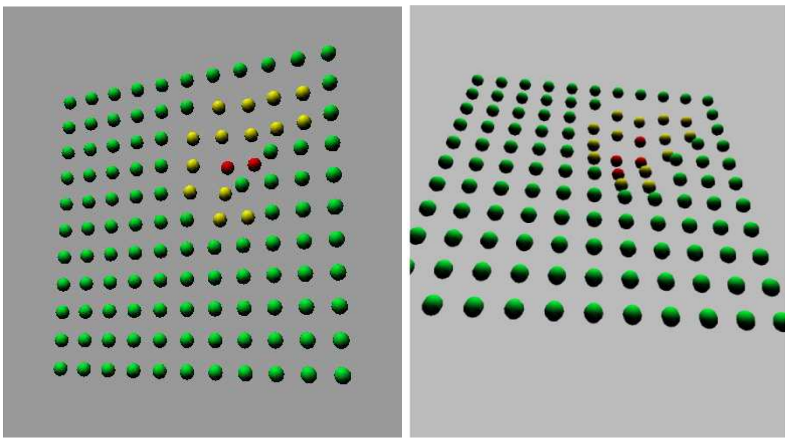
The system designed to make the data collected by the sensor of the PoliBeetle be visible in a easy and clear way is a 3D representation of the surface inspected, with different colours to identify the various heights of the surface and find the anomalous depressions. We made it with a web application coded with the JavaScript language.

How the programm works

The program, that can be on board if there is a crew who can check a computer screen or be used at ground control centers, works collecting the data coming from a database installed on the PoliBeetle and representing them in cartesian coordinates.

The PoliBeetle is capable to recognise with his sensor the heights of various points of the surface (the number of points depend on resolution), collect them in a database and suddenly sending it the to webapp which inserts those data in his 3D reference system.

Each point is respresented as a small coloured sphere; the colour depends on the height of the point: it goes to red as the deep of the depression became more and more.



Images taken from the app showing a small depression caused by a possible debris

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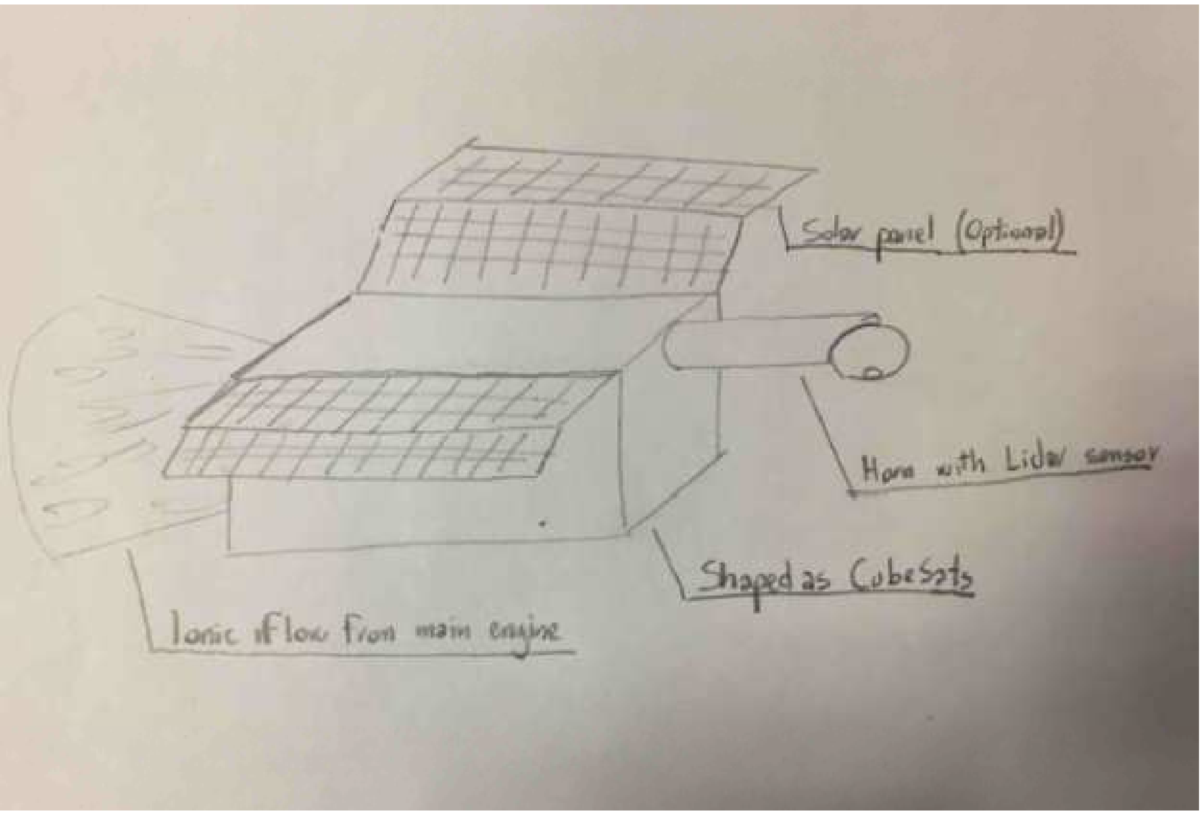
CHAPTER 5:

FINAL CONCEPT OF PoliBeetle-7



END