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DESIGN OF AN INTEGRATED HAPS DETECTION SYSTEM

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ABSTRACT

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El desarrollo de nuevas tecnologías en el ámbito de las telecomunicaciones genera un gran impacto en como nos comunicamos con otras personas y hasta con algunos objetos. La incorporación del 5G, el IoT y el 6G necesitará nuevos medios de transmisión que puedan proveer a la población mundial de internet de banda ancha sin apenas latencia.

Uno de esos nuevos medios son los HAPS, prototipos aún, que ofrecerían una solución a la hora de ofrecer internet en áreas remotas, zonas afectadas por conflictos o desastres medioambientales, además de servir de apoyo en grandes ciudades en situaciones de picos de tráfico.
Pero de la misma manera que dicha tecnología tiene grandes beneficios para la humanidad, cayendo en las manos equivocadas podría comprometer la privacidad de las personas, en cualquier parte del mundo.

El estudio se enfocará en aplicar un sistema que permita detectar HAPS que entren en un espacio aereo para comprobar si éstos han sido autorizados o no, así como también se profundizará en el concepto de HAPS y su posible utilización en los próximos años, haciendo una comparación con otros proyectos similares que rivalizarían con los HAPS

The development of new technologies in the field of telecommunications has a great impact on how we communicate with other people and even with some objects. The incorporation of 5G, IoT and 6G will require new means of transmission that could provide the world population with bandwidth internet with close to zero latency.

One of these new means is HAPS, which would offer a solution when it comes to bringing the internet to remote areas and zones affected by conflicts or environmental disasters. HAPS could also serve as support in large cities in situations of network traffic peaks.
Although such technology has great benefits for humanity, falling into the wrong hands could compromise the privacy of people, anywhere in the world.

The study will mainly focus on applying a system that allows detecting HAPS that enter an airspace to check whether they have been authorized or not, but also it will deepen into the concept of HAPS and its possible use in the coming years, as well as making a comparison with other similar projects that would compete with HAPS

CONTENTS

PREFACE

Before introducing my bachelor's thesis, I would like to contextualize why I think this topic is pretty special for me.
In the last year of my studies in Aerospace Engineering, I chose to major in Air Navigation, a field in telecommunications that always triggered my thirst of knowledge. When during the last months I discovered how important is internet for everybody and how having connection to the net can help hundreds of millions of people in undeveloped countries, I started concerning about bringing internet worldwide. A person with a smartphone, anywhere in the world, can access any kind of information and educate themselves, develop their ideas or have control over their finances via blockchain. Basically, can break down the barrier that separates 1st World from 3rd World.

My original idea was to use airplanes as regenerative satellites, to provide internet while the aircraft is overflying an area, but not so many planes fly over Africa for instance, so once I discovered the concept of HAPS, I found it was a very interesting topic to work on, hence, I was excited to do my thesis to introduce people to HAPS.

ABBREVIATIONS AND TERMS

ADS-B	Automatic Dependent Surveillance-Broadcast
DL	Downlink
EIA	Environmental Impact Assessment
ESA	European Space Agency
IoT	Internet of Things
LEO	Low Earth Orbit
LoS	Line of Sight
PRF	Pulse Repetition Frequency
RCS	Radar Cross-Section
SDR	Software Defined Radio
SORA	Specific Operations Risk Assessment
RF	Radio Frequency
RPAS	Remotely Piloted Aircraft System
SMS	Short Message Service
UL	Uplink
URLLC	Ultra Reliable Low Latency Communication
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
VFR	Visual Flight Rules

1. INTRODUCTION

During the last decade, with the mass adoption of the smartphone, internet has become a necessity for a huge part of the population worldwide. Any person with a smartphone is able to communicate with anyone in the world, have a bank account, apply for jobs, invest, start up a company, etc. Although in the last years the vast majority of the world has access to internet, there are still some areas, specially remote places in undeveloped countries or warzones where such access is difficult or even impossible.

Companies have been working on different concepts to cover such problem, and one of these ideas is the usage of HAPS.
HAPS, pseudo-satellite located in the stratosphere, provide services, such as internet, to users that don't have a ground station near, as well as serving as a back up for the rush hours in big cities. Furthermore, there are other usages outside of the telecommunication's sector, like checking pollution, assisting fire fighters in forests or tracking criminal activities.

Although the usage of such concept would be used mainly to improve the life quality worldwide, it leaves the door opened to misuse it by criminals, as already happened in the 2010s when the commercialization of drones allowed criminal usage, using drones to spy, send weapons to prison or to disturb airplanes when approaching the runway.

The goal of this thesis is to introduce the concept of HAPS and its possible uses in the following years, as well as raising awareness regarding the need of starting to develop detection systems before HAPS gains popularization and illegal activities start to be carried out, as already happened with drones.
In the following pages, HAPS will be introduced and different solutions to detect them will be explored based on previous research on drone detection. A first approach to design a HAPS detection system using a combination of radiofrequency and radar will be intended.

2. HAPS

2.1. Background

There has been a tremendous revolution in the last 30 years in the field of telecommunications, specially in the mobile telecommunications. The first phones using 1G could only be used to make calls. In the 90s, the 2G came allowing to use a mobile device to also send SMS. 3G gave access to mobile phones to internet in 2004, leaving the door opened for the invention of the smartphone. 4G followed bringing high speed internet to such devices, allowing to listen to music and watch films streaming, and recently, the deployment of 5G is allowing ultra-high speeds and very low latency, that will introduce the IoT era.

One solution that companies have been researching lately was the usage of HAPS, which stands for High Altitude Platform Station or High Altitude Pseudo Satellite. They operate in the stratosphere at around 20 km high. Unlike satellites, which must orbit and therefore, unless when in geostationary orbit (GEO), continuously change location, HAPS have the ability to be quasi stationary, working as a geostationary satellite but without orbiting.
Due to their relatively close distance to the Earth surface, communications using HAPS are two or even three orders of magnitude faster than satellites. This feature makes HAPS ideal for Ultra Reliable Low Latency Communication (URLLC)

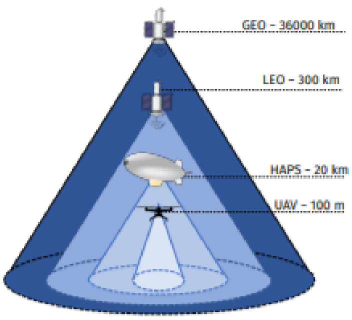

Figure 1: Different layers of telecommunications(Source: [1])

These UAS work as a second layer for satellites. While a normal user would have to first connect to a ground station and later such station connect to the satellite, a user using a HAPS as an intermediate layer, would connect directly to the HAPS, not having to rely on a ground station, as well as making the radiolink significantly shorter.

This technology is specially helpful in areas where these ground stations are inexistent or not updated, as happens in remote areas such as the Poles, some islands, unpopulated mountain areas, etc. But people living in undeveloped countries or areas affected by wars are the ones that benefit the most, as otherwise their connection to internet would be inexistent.

Internet connection in these countries are specially important, since anyone with a smartphone with internet connection is capable of communicating to anybody, anywhere, as well as searching for a job, creating a company, educating themselves and one of the most important issues, being able to be their own bank, using blockchain technology. Internet has the ability to break down the wall that separates the 1st World from the 3rd World, making everything accessible to anyone. In *Figure 2* we can observe how HAPS could bring 5G to remote areas, as well as a HAPS providing support to a cluster of drones.

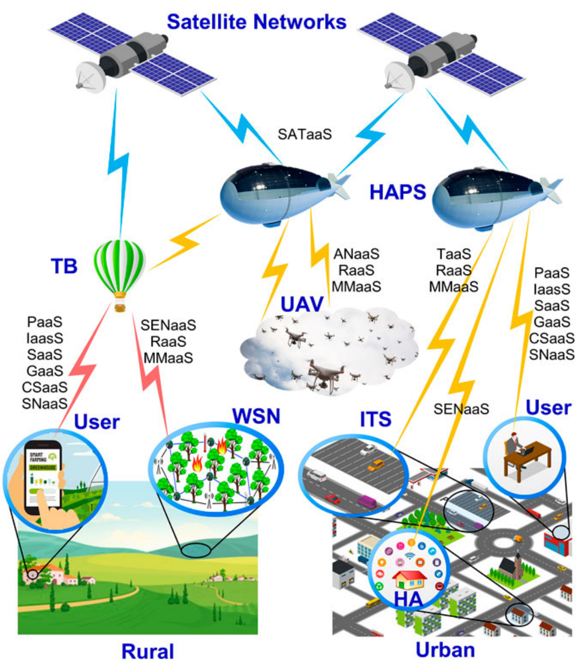

Figure 2: HAPS giving service to remote areas, as well as providing service continuity in a city. (Source: [1])

HAPS also allows the implementation of new uses of drones, like delivering packages in cities by air, as Amazon started to experiment with. When flying hundreds of autonomous drones in the U-Space, it's crucial that they can react

as soon as possible when facing some hazards, such as encountering with other drones (even unauthorised drones), birds or other aircrafts. A collision in mid air of two drones over a crown of people would be extremely dangerous, either for the people below and for the reputation of the company.
For this reason, the usage of a HAPS as a main station for such drones in order to provide them with almost instant data would be crucial.

Other usages of HAPS are tracking forest fires, pollution, or looking for suspicious activities such as illegal immigration, illegal fishing, drug trafficking, etc. [5]

2.2. Types of HAPS

There are two main different UAVs that can be used as HAPS, electric airplanes and stratospheric airships.
Some reasons to fly in the tropopause are:

- Flying high enough so they do not interfere with commercial and military aviation.
- Avoiding the huge winds that are caused by the jet stream.
- Getting direct sun radiation, avoiding clouds and any other meteorological phenomena, in order to fuel their solar cells

Electric airplanes

They are unmanned ultra light aircraft powered by solar cells that can easily be deployed and can remain flying over a designated area for as long as 2 weeks. They are easily maneuverable and can change location using flight control surfaces.
Weight is a critical element as electrical airplanes have a very limited thrust, only capable of carrying very small payloads.
In addition, these UAS must carry batteries that would charge during the day, allowing them to fly during all night.

Figure 3: Artistic representation of the Airbus Zephyr T (Source: ESA, [2])

Airships/Balloons

They are geostationary balloons filled with lighter-than-air-gas. As they don't need any propulsion, they can stay many months flying over the same position without needing to go back to ground. These UAS use solar panels in order to be able to transmit radio frequencies and in order to maneuver. They can carry bigger payloads that airplanes as their lift is not generated by an electric propeller but by buoyancy.

Batteries are needed to keep operating during nighttime.

Figure 4: Representation of a futuristic HAPS (Source: ESA, [3])

3. DETECTION SYSTEM

Although HAPS can be a very powerful tool for humans, they can also be used against them, specially violating people's privacy by recording in high definition people's personal life, tracking their movements and private lives. Unauthorized UAS can be a physical threat to another UAV, aircraft or people when not following the SORA (Specific Operations Risk Assessment) [6] as they could enter in restricted airspace, thus interfering in the airspace designed for aviation provoking close calls with aircraft.

A study by the Center of Study of the Drone at Bard College reported 921 cases of encounters between manned aircraft and drones between December 2013 and September 2015, only in the US [7].

For these reasons, it is key to find a way to spot HAPS and to catalog them as authorized or not authorized and thus, taking measures against the latest ones.

3.1 System requirements

- The system should be able to detect radio frequency transmitted by HAPS up to 1505 MHz
- The system should give an approximation of the HAPS position in the three dimensional-space
- The system should be scalable, robust and work uninterrupted 24 hours per day in any meteorological condition

3.2 UAS detection overview

Multiple researches have been done in low altitude UAVs [13], [14], [15], [16] & [17]. Giving 5 main different methods to spot UAVs. Since HAPS is a very new concept and there are only prototypes, no research has been already done regarding detecting HAPS, hence we will start our research using previous research carried out on UAVS in the last years and adapt that to HAPS. In the following subchapters we will explore the 5 most used methods to detect drones and discard the ones that are totally non-viable due to some huge differences between HAPS and drones.

3.2.1 Acoustic detection

One of the main ways of detecting drones is by the sound generated by the air displaced by their engines. That sound can be heard by using a microphone and then be compared it to other sounds stored in the database. This method has a low range of action, but it's very effective as can act in all directions, covering a decent volume of air from where the microphones are placed. Acoustic detection also works in noisy environments, as long as the drone's frequency is different from the surrounding noise. The main problem with acoustic detection is that since sound's power decay very fast with distance, only very low flying UAVs can be detected. Although this method is highly effective for drones, it will have to be discarded for detecting HAPS, as they are generally silent and flying in the stratosphere, impossible to be heard by any microphone.

3.2.2 Visual detection

This method is very similar to the acoustic detection, as both are based on sensorial detection. In this case, a set of cameras will be used in order to take pictures of the surroundings to compare them in a database. It can be used for drones, helicopters and airplanes, but hardly used for HAPS due to the distance and relatively small size compared with commercial airplanes. In addition, this method needs a Line of Sight (LoS), which makes long-range detection impossible when the sky is not totally clean of clouds. A last con in order to use this method to detect HAPS is that the system needs to have a previous record of the flying object, making the system useless for designs that aren't made public.

3.2.3 Radar detection

Radio detecting and ranging systems is the most common used method for detecting any kind of flying object. An antenna transmits short beams at high frequency and compares it with the echoes received. It can detect direction and velocity of flying objects, as well as animals and clouds. Regarding HAPS detection, this technology could be used for detection of airships, due to their spherical/cylindrical shape, but hardly used for airplanes, as their radar cross-section is very low since they have very thin structure, as seen in *Figure 3* The usage of a Doppler radar wouldn't be suitable as HAPSs move at a very low speed.

3.2.4. Radio frequency detection

Radiofrequency: UAVs are extremely dependent on telecommunications. In case of RPAS (Remotely Piloted Aircraft System), the UAV needs permanent connection with the controller in order to navigate. Autonomous UAS need data links in order to send data to the ground, which as all telecommunications nowadays, are handed via radiofrequency.

While electronic components, such as spectrum analyzers, designed for telecommunications are normally expensive, there are cheap alternatives like Software Defined Radios (SDR), which for as low as 20 €, can scan a spectrum from few kHz up to around 2GHz. The usage of SDR will be explorer as a cheap and reliable tool for RF detection.

3.2.5 Thermal detection

All mechanical devices produce heat due to energy losses due to Joule's effect. It's easily detectable if a machine has been utilised recently by using a heat detection system that can detect infrared radiation.

While this method could be used for drones, the usage in HAPS is not practical due to these UAS not generating much heat as moving at low speeds (or sometimes even not moving at all, in the case of the balloons). Furthermore, the range of detection can't match the distance at what HAPS fly. Hence, this method must be discarded.

3.3 Scope

The detection system consists of two subsystems, a radiofrequency detector that would allow detecting HAPS entering a defined area and give a rough approximation of the distance between the receptor and the HAPS and a radar subsystem, that would serve in two different ways; as a backup from the RF and as a detector of the position of the HAPS. Once a UAS is detected by both systems, it should be compared in a database with all the authorized UAS and if there is no match, the information should be reported as a potential unauthorized HAPS.

3.4 Assumptions

The principal assumption will be that there won't be any big electromagnetic radiation in the surroundings of the operative area of the HAPS. This is a fair assumption as one of the main usages of HAPS is to bring internet to remote areas, where there isn't any kind of telecommunications. Hence, the part of the electromagnetic spectrum we would operate would be free of radiation.

We will also assume that there will not be extreme weather conditions, such as heavy precipitation.

It is also assumed that only commercial HAPS will be detected, since military ones would use mechanisms to hide their transmissions such as frequency hopping. They could also be stealth, having a very low RCS, undetectable by radars.

There should also be a regular supply of electricity available in order to operate the system.

3.5 Safety

The detection system, with all its components (antennas, computers, electrical circuits) should be safe and never be a hazard for people. There should be emergency systems shutdowns easily visible and users must know how to activate them (for example a button for shutting down). All components should be adequately labelled, so no misuses could happen due to unawareness.
Structural elements such as the antenna for RF or the radar must be fixed to the roof and secured so extreme weather conditions wouldn't cause a threat to human lives (such as antennas breaking off and falling to the ground due to heavy wind).
All devices must be treated adequately once their lifespan expires, following the indications given by the EIA (Environmental Impact Assessment).

3.6 Material

The system for HAPS detection will consist of two different subsystems. The primary subsystem and the secondary one. The primary subsystem will be a Radio Frequency detector which will be scanning the airspace looking for any potential UAS. Using the CT1FFU DXPatrol SDR Rx (*Figure 5*) we would be able to scan the spectrum from 100kHz to 2GHz, covering the whole spectrum used by the HAPS, which for downlink ranges from 324MHz to 1505 MHz.

Figure 5: CT1FFU DXPatrol SDR

In order to process the information from the SDR, we will need a computer and a software designed for SDR, such as “SDR sharp” *(Figure 6).* SDR# is a free open source software that allows to easily visualize the frequencies detected by the SDR, showing the noise level and the signal power, which allows to get a visualization of strong and weak signals, calculate SNR, etc.

Signals coming from UAS will be represented with a big peak as their high Signal to Noise Ratio. Other signals will be hardly visible and could be seen as noise.

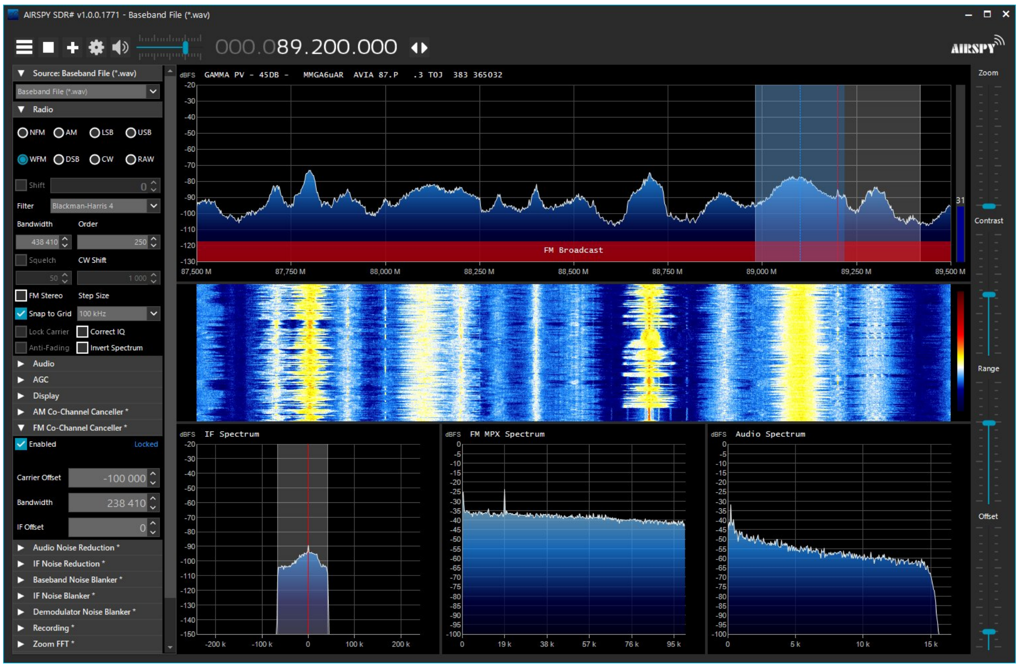

Figure 6: Interface of the SDR Sharp software

These frequencies will be detected by an antenna such as the Mars 138-6000MHz an Ultra Wideband omnidirectional antenna *(Figure 7).*

This antenna is ideal as we need a non-directional antenna (since we have to explore 360º), as well as being ultra wideband, allowing the usage of only one antenna for our purpose, for a very accessible price.

The antenna must be placed outside the building where our detection station would be set.

Figure 7: Mars 138-6000MHZ

Radar materials will not be studied here as these systems are very complex and their price rounds some tens of thousands of Euros.

3.7 Detection via radio frequency

3.7.1 Background on radio frequency

Since the main purpose of a HAPS is to transmit information in real time to the ground and such information can only be transmitted via radio frequency, we will use this advantage as the main way for detection.
We will focus on the communication HAPS-Ground station/user, known as downlink, and will work on detecting the signals coming from the HAPS' telecommunication channel.
According to some research [8] the bandwidth required for the uplink (ground-to-HAPS link) comprises from 396 MHz to 2969 MHz and the bandwidth for the downlink (HAPS-to-ground link) from 324 MHz to 1505 MHz, both allocated in the spectrum of Ultra High Frequency (UHF).

In addition, at the World Radio communication Conference in 2019 (WRC-19), the bands 31 - 31.3 GHz and 38-39.5GHz were allocated for the HAPS usage, being added to the current 47.2-47.5GHz and 47.9GHz-48.2GHz, which are used worldwide, and the 2-6GHz band dedicated to International Mobile Telecommunications (IMT).
Other bandwidths, such as 21.4 - 22 GHz and 24.25 - 27.5 GHz could be used in North and South America.

Frequency band	Frequency range (GHz)	Wavelength range (cm)
L band	1–2	15–30
S band	2–4	7.5–15
C band	4–8	3.75–7.5
X band	8–12	2.5–3.75
Ku band	12–18	1.67–2.5
K band	18–27	1.11–1.67
Ka band	27–40	0.75–1.11
V band	40–75	0.4–0.75
W band	75–110	0.27–0.4

Figure 5: Microwave bands (Source [9])

On the other hand, due to the size similarities between the wavelength and water drops, attenuation in bad weather conditions primarily affects high frequencies. Although the HAPS are located in the stratosphere, a big part of the radio link takes part in the troposphere. As seen in *Figure 6*, precipitations can significantly affect the quality of the communication channel used by HAPSs.

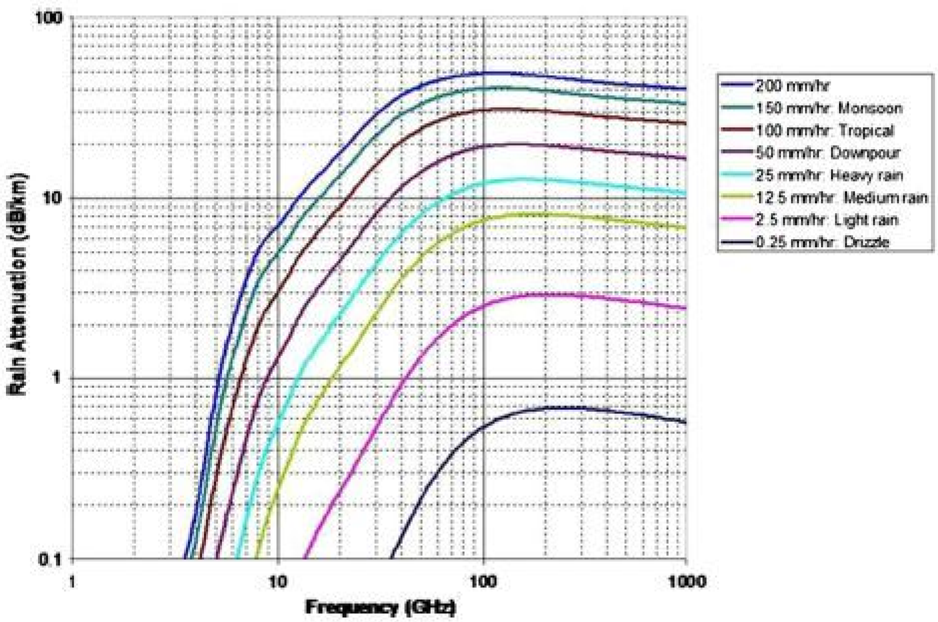

Figure 6: Rain attenuation across Frequency at various rainfall rates (Source: [10])

In order to achieve Radiofrequency detection, we need to understand the HAPS Link Budget. In *Figure 7* there's a schematic of a system transmitter-receiver, where factors as the gain of both antennas (transmitter and receiver) are accounted, as well as the losses experienced due to free space and rain-fading. Both the carrier signal and the noise are represented as a function of time “n(t)” and “s(t)”, respectively, until they get represented as CNR (Carrier-to-Noise Ratio).

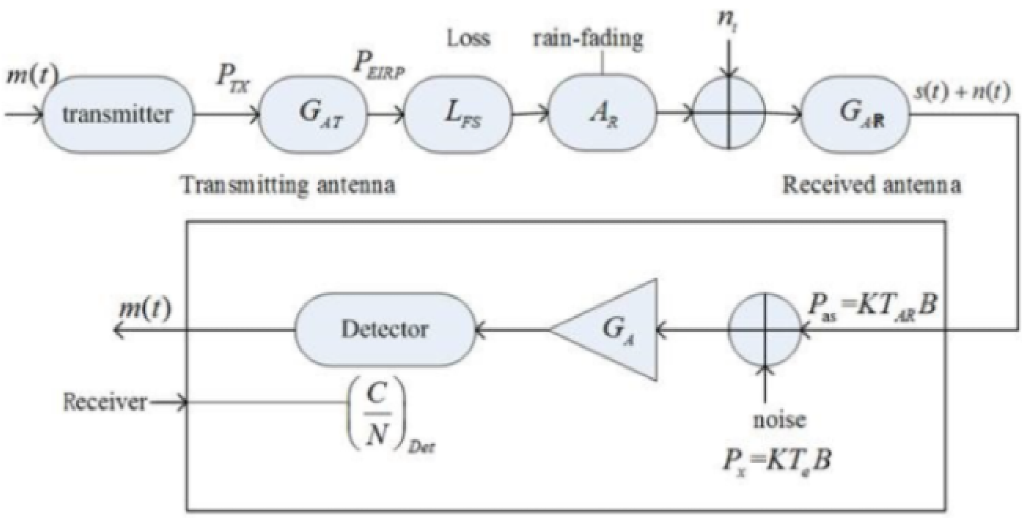

Figure 7: HAPS Link Budget (Source: Alejandro Aragon-Zavala, 2008)

One of the most important parameters in telecommunications is the SNR (Signal-to-Noise Ratio) or CNR , as it shows the quality of the signal. The bigger the SNR/CNR, the better the quality of the signal. It is measured in dB.
The equation of the CNR in dB is the following:

$$CNR_{dB,DL} = EIRP_{HAPS} - L_{FS,DL} - A_R (G/Ts)_{dB,ES,fom,/k} - k_{dB} - R_{dB,DL}$$

where:

- EIRP = Equivalent Isotropic Radiation Power
- L_{FS} = Free Space Loss
- G/Ts = Figure of Merit
- R = Receiver Loss
- k = Attenuation

Being the Free Space Loss as follows.

$$L_{fs} = \left(\frac{c}{4\pi fD}\right)^2$$

For a frequency of 28GHz, in the Ka band, a vertical distance between the HAPS and the user of 20 km and an angle between them of 70º, we obtain a distance of the radiolink of around 60 km. Hence, the free Space Loss is around 160dB.

Taking a EIRP from the HAPS of 30dBW, a receiver loss of 2.5 dB and an atmospheric gas attenuation of 0.4dB, we end up with a CNR of 77dB. This can be considered as an excellent signal.

Since most of the telecommunication satellites are in geostationary orbit, it is fair to compare their data link with HAPS.

A regenerative geostationary satellite, transmitting power of 16.5dBW [11] with an standard antenna gain of 13.5dBi, the resulting EIRP is 30dBW. Such radio link would lose an extra 60dB in Free Space Loss, leaving a CNR of around 7dB, a difference of 70dB between HAPS and satellites in GEO.

3.7.2 Receiving power calculation

Once we have concluded that it will be easy to difference a signal coming from a satellite than one coming from a HAPS, just by comparing their power, now we can calculate a range of received powers at different distances in order to filter later the signals.

When the system detects a radio frequency that could be emitted by a HAPS, The distance can easily be calculated when using the Friis transmission equation

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \qquad \lambda = \frac{v}{f}$$

Where:

P_t = Power transmitted

G_t = Gain of the transmitter antenna

G_r = Gain of the receiver antenna

v = Speed of the signal

f = frequency

R = distance between the antennas

Some operations will be done in order to find the range of power that the system would detect, and from there easily filtering out the frequencies that could be generated by HAPS from the background noise (signals generated by satellites).

Two different ranges will be calculated, one for each height limit at which HAPS can be located. These ranges will be taken into consideration now.

Four calculations will be made, one for the minimum frequency and minimum range, one for minimum frequency and maximum range, one for maximum frequency and minimum range and another one for maximum frequency and maximum range. Speed of the signal will be considered the speed of light. Frequencies will be 324 MHz and 1505 MHz and ranges 113 km and 283 km. Both antennas will be considered equal and will have the gain seen in the antenna's data sheet [*table A.1*]. Power transmitted will be assumed as 44.5 W, same as for the geostationary satellite [11], although power varies depending the type of satellite, their age, functionality...

Gain for 324MHz will be assumed 4dBi as this frequency doesn't show in the data sheet

Range	Frequency	Gain antennas	power received
113 km	324 MHz	4dBi	-99.2 dBW
113 km	1505 MHz	8dBi	-104.6 dBW
283 km	324 MHz	4dBi	-107.2 dBW
283 km	1505 MHz	8dBi	-112.5 dBW

Once we know the sensibility that our system would have (from -99.2dBW to -112.5dBW), we can now apply a dynamic range, set at the peak of -99.2dBW of around 40 dB *(Figure 7)* which would allow us to filter noise while leaving the ones sent by the HAPS. The minimum received signal then would be of around -139.2dBW once applying the dynamic range. This would filter a big part of all

the data received from satellites, specially the ones in GEO, which have the lowest receiving power due to what has been stated before.
Note that our detector would still detect other signals that are in the same range, such as satellites in LEO (although the signal would be detected as noise due to the low receiving power).
Hence, the 70dB difference in SNR between satellites (in GEO) and HAPS will be key in order to spot UAS.

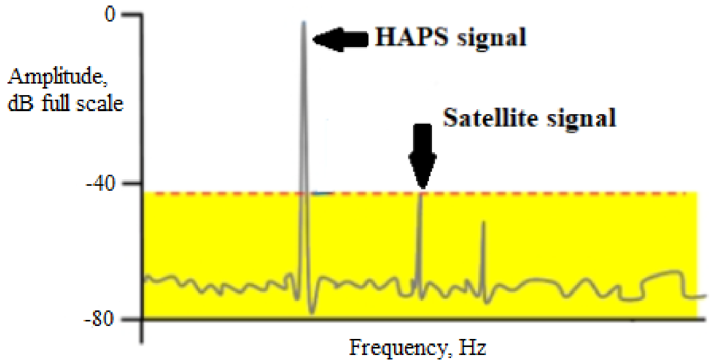

Figure 7: Dynamic range of 40dB that filters satellite signal.

3.7.3 System characteristics

3.7.3.1 Uncertainty

Before presenting the next section, we must first introduce the concept of uncertainty, and why it will be a key factor in the detection of HAPS.
Uncertainty is the lack of certainty when detecting a UAS. Uncertainty will be present in 3 different dimensions: linear distance, area and volume. The more constrains we can add, the lower the variables, hence the dimensions of uncertainty and the greater the accuracy.
We would also use two different terms:

- Horizontal uncertainty when referring to the 1D (linear distance dimension) distance from the station to the detected object, using a plane tangent to the surface of the Earth

- Vertical uncertainty, also 1D, that would mean the distance from the object to the surface of the Earth, the height.

3.7.3.2 Range

The horizontal range of detection of our system would be determined by the observation (elevation) angle and the height of the UAS. To calculate it, we took the minimum and the maximum height at what HAPS operate and by simple trigonometry, calculate the horizontal distance our system could theoretically cover. In case the base station would be in flat terrain without significant elevation we should choose a minimum elevation angle of 10º to be conservative, although we will explore how would it be in a hypothetical case where the station could be set on the top of a mountain. .

We calculated two minimum distances, one for HAPS located at the minimum altitude (20 km), which as seen in *Figure 8* it's 113 km and another minimum for HAPS located at the maximum altitude (50 km), *Figure 9*, being 284 km.

Hence, our system will have a horizontal range between 113 and 284 km, which is considerably good.

Note that the range is between the 2 values since it wouldn't be possible to detect a HAPS flying at a height of 20km at a longer horizontal distance than 113 km, due to trigonometrics.

As we are applying a decent elevation angle, we don't have to take into account the curvature of the Earth, thus we can use the flat earth model.

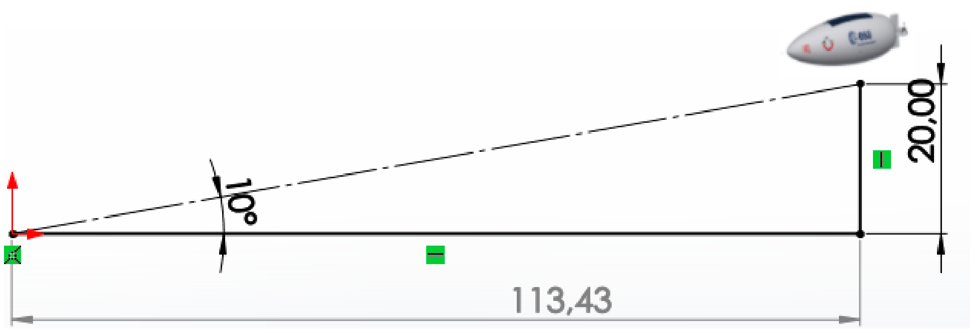

Figure 8: Horizontal distance for 10º elevation and 20 km height. Perpendicular to Earth axis.

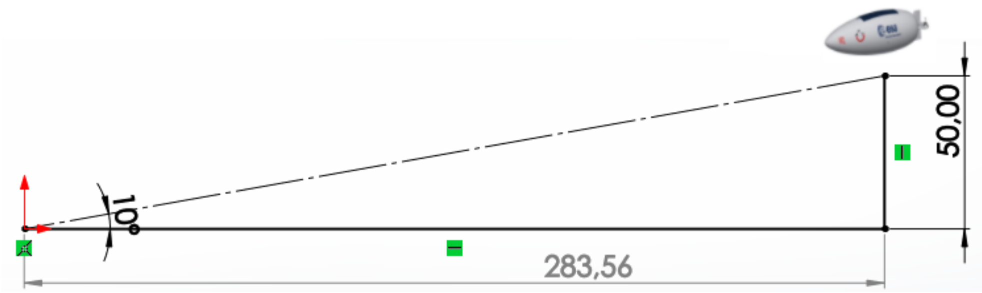

Figure 9: Horizontal distance for 10º elevation and 50 km height. Perpendicular to Earth axis.

3.7.3.3 Minimum range

There is a big constraint upon detecting HAPS and this is the minimum detecting range. When a RF is detected and by the power received, the real distance to the object is calculated, but in order to detect the UAS, we need the horizontal distance.

When the distance from the station is lower than 50km (the upper space constraint), the uncertainty of the HAPS location is maximum, as it would be a volume of a semisphere of radius equal to the detection distance. The object though, can be located at a height between 20 and 50 km, leaving a degree of freedom, as height remains as a incognite. As seen in *Figure 10*, a signal coming from a HAPS at 48km could be located anywhere between 25º to 155º.

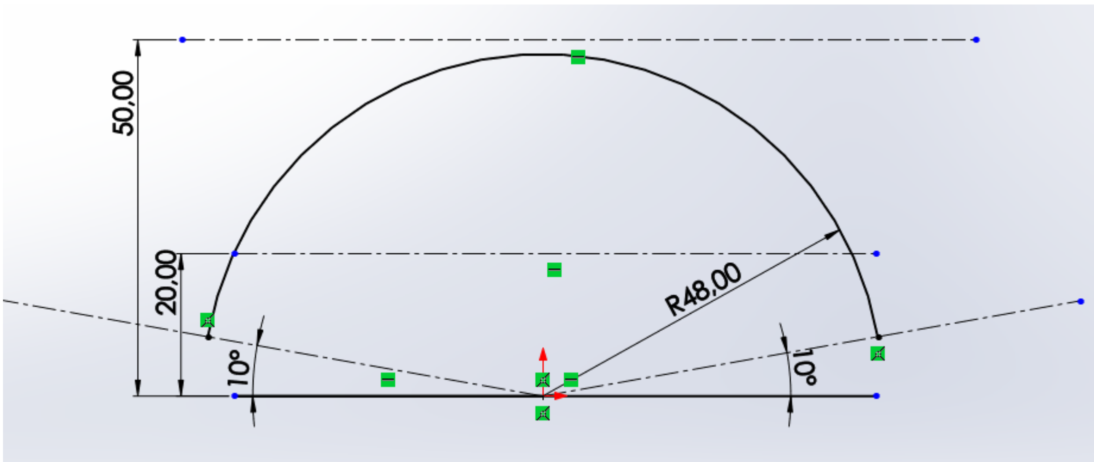

Figure 10: Representation of 160º of uncertainty. Perpendicular to Earth Axis

In the figure above, the HAPS horizontal incertainty is:

$$x = 48 \cdot cos(25º) = 43,5\ km$$

meaning that the HAPS could be either in the zenith, right on top of the station with a horizontal distance of 0 or as far as 43.5 horizontal km if the angle with respect to the station is as low as 10º.

Hence, in order to define the accuracy of the detection, we must set a minimum detection range, which at least it must be bigger than 50 km. The bigger the minimum range, the lower the uncertainty will be. When for instance detecting an object at 113 km (the maximum range for 10º and 20km high), the uncertainty is 9.95 km (as the HAPS could be located in between 20 and 50 km) as seen in *Figure 11.*

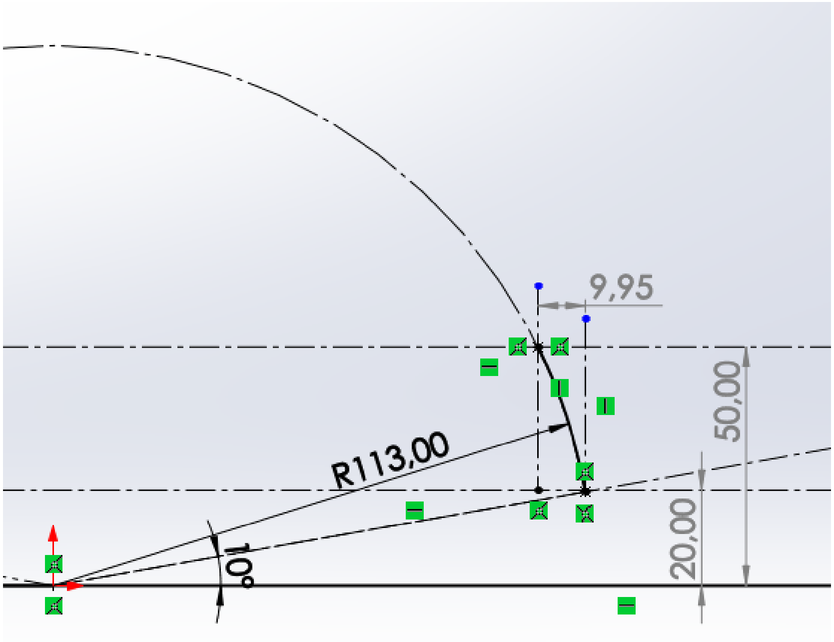

Figure 11: Representation of the horizontal uncertainty. Perpendicular to Earth axis.

Theoretically, the only point at which the uncertainty is zero (and hence, the accuracy is higher) is when the minimum range matches the maximum range, since there aren't any more incognites. That point would at 283 km horizontally and 50 km vertically. In that moment, the volume of the uncertainty would become zero and the a dimension would be decreased.

We meet another constraint: the bigger the minimum range is, the bigger, the lower altitude will be. As calculated before, a minimum range bigger than 113 km would stop detecting HAPS located right at 20 km.

For a reasonable uncertainty of 1 km (a volume of a disk with a width of 1km), the distance must be greater than 258 km, only 25 km smaller than the maximum range for 50 km high. In order to lower the huge minimum range, more constrains will have to be taken, such as either placing the station in the top of a mountain so the elevation angle can be set at 0º or that we would focus on the HAPS that are the closest to the ground.

A problem about the RF detection is that the signal is coming from 360º, hence there will be an area of probability where the HAPS would be. As seen in *Figure 12* the area of the circle represents where the UAS could be located, for a distance of 113 km in a 360º environment.

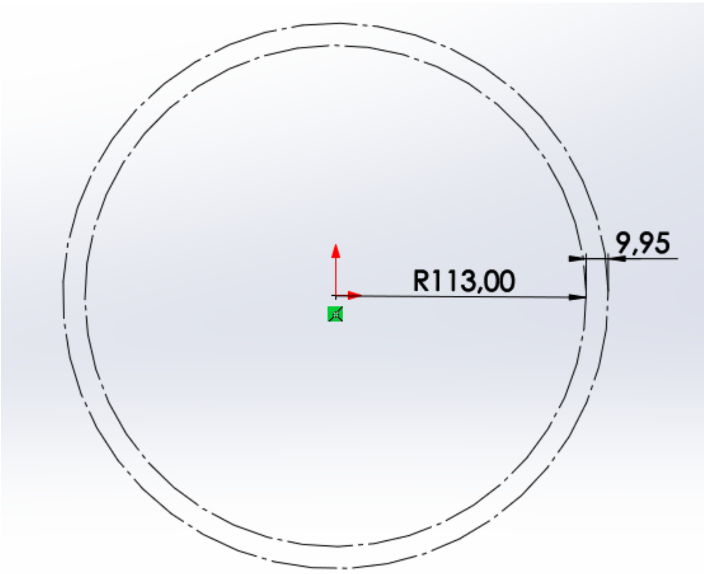

Figure 12: Representation of the area where HAPS could be detected at maximum detection range for 20km high. Tangential to Earth axis.

It's important to note that all these values have been taken considering the theoretical strength of given signal, but in reality many factors can change the strength, adding another uncertainty, such as the presence of rain as seen in *Figure 6,* the attenuation due to the atmosphere when detecting a HAPS at a large distance and at a very low angle of elevation, problems with antenna's gain, which would reduce the signal received or transmitted, the addition of surrounding noise…

A way to highly reduce the uncertainty would be to reduce the vertical range of detection, from 20-50km to somewhere around 20-25km high. This is the altitude most of the HAPS are expected to fly and by just focussing in a segment of all HAPS, the accuracy of the system would be considerably increased.

3.7.4 Alternatives

As we have seen in above, setting the station in a flat terrain would have two big constrains, the minimum range and the actual range at which it would have a uncertainty low enough to consider the method. For such reason, we contemplate two different alternatives, either locating the station on the top of a mountain to scan at 0º elevation and using a radar or setting more stations at different locations to make a triangulation without a radar system. We will develope both.

3.7.4.1 System on elevation

The biggest problem when locating the system in a flat area is that we must observe the flight at a certain angle of elevation, since the radius of the Earth is huge compared to the distances we want to cover. For such reason, setting the station on the peak of the highest hill in the area would allow us to scan at almost 0º of elevation.

In *Figure 13,* we can observe the theoretical maximum range for both, 20km high and 50km high at a elevation angle of 0º, which is considerably bigger than in the case studied above. These ranges are limited due to the Earth being spherical, so we can't consider the flat Earth model.

Note that the tangent lane represents the angle of elevation at a height of 0m (considering that we would be at the highest peak). This is theoretical as in very few locations, a height of 0m is the highest, but for sake of simplicity, we would calculate the theoretical maximum range this way, as the higher the height, the lower the range of detection.

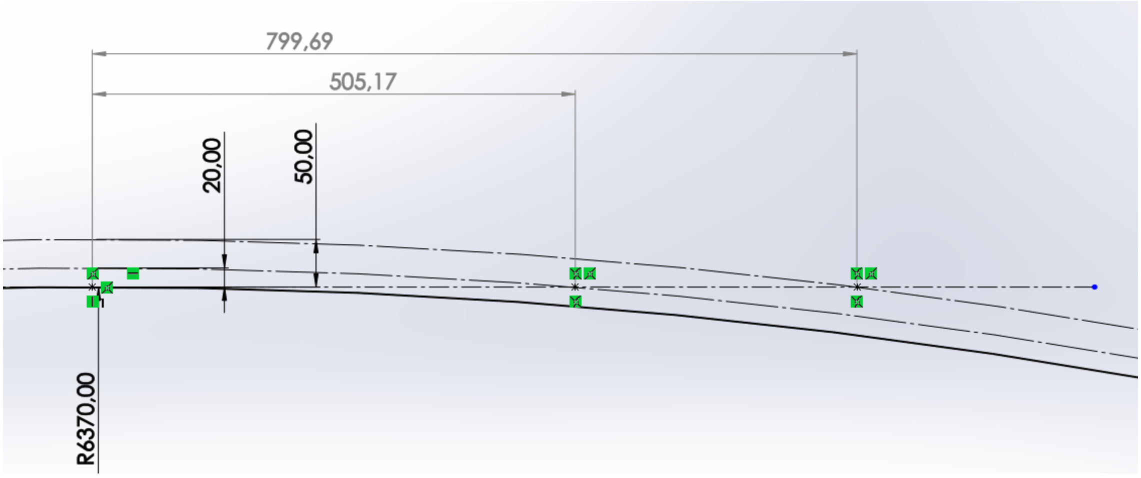

Figure 13: Maximum ranges for 0º elevation. Perpendicular to Earth axis.

The two maximum ranges are 505 km for the lower height and 800 km for the higher one. These are significant bigger than when they were placed without taking into account the height of the station in relation with the environment.

Although the situation is significantly better than in the case studied before, when we set a horizontal uncertainty of detection lower to 1km, we find that the distance to the UAS has to be greater than 490km, only 15km lower than the lower maximum range (505 km), as seen in the *Figure 14*, which still makes the system not accurate.

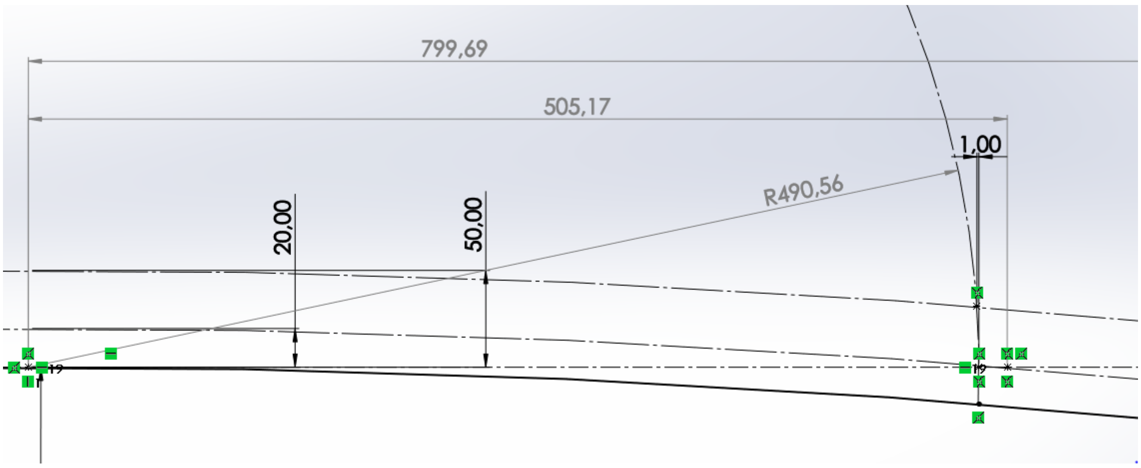

Figure 14: distance at where the horizontal uncertainty is lower than 1 km. Perpendicular to Earth axis.

Even when the system is located at the highest point of the environment, a secondary system, a radar, must be used.

3.7.4.2 TRIANGULATION

A way to solve the problem of the uncertainty distance of detection would be to use the triangulation method, which has been used for already 2,000 years. This method consists on placing at least two stations separated few kilometers. When an object enters the area of detection of both stations, both will detect it and compare the distance from each station to the object.

Since the distance at a certain point from the UAS to the two stations would be a fixed value, we would achieve two things: eliminating the horizontal uncertainty, as now we could detect the exact position vertical distance to the ground as well as eliminating the 3 different dimensions (linear, area and volume), since now the system would give only two different possible locations of the UAS.

As observed in *Figure 15,* the system would detect two points in the vertical component, but only one would be feasible, as the other would always be underground, hence automatically discarded. On the other hand, the system would give two possible horizontal locations, as observed in *Figure 16.*

Note that even though both figures might look the same, they are representations of different planes, one tangent to the surface of Earth (*Figure 16*) and the other perpendicular (*Figure 15*)

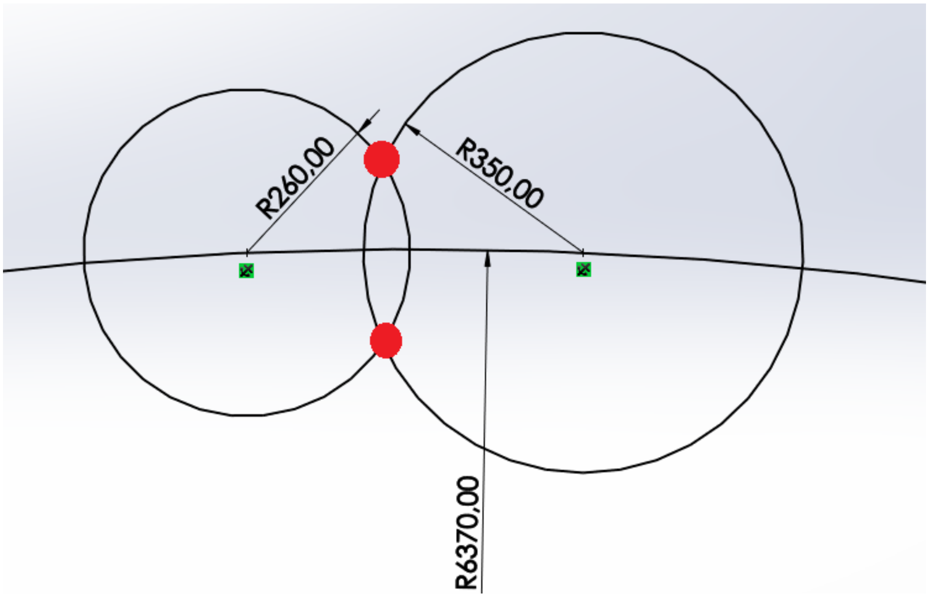

Figure 15: Representation of the vertical distance. Perpendicular to Earth axis.

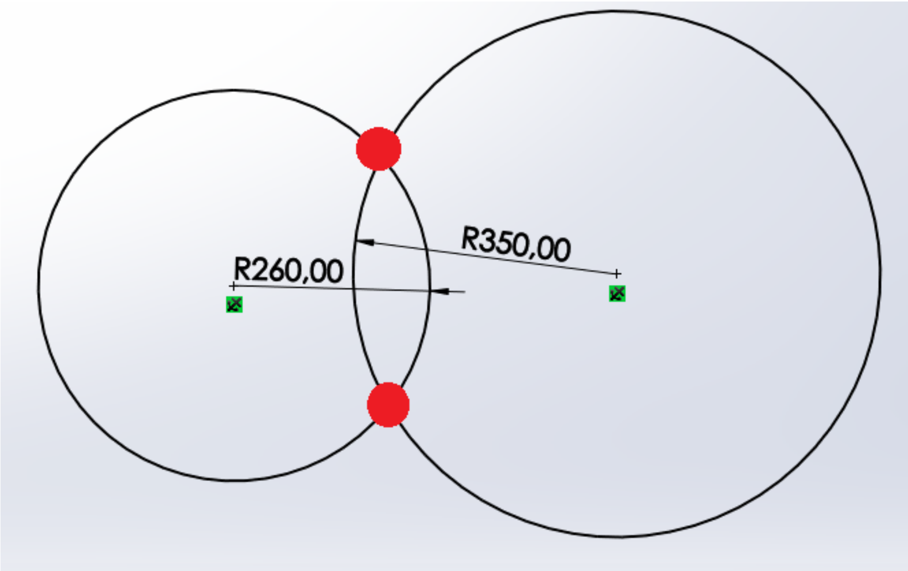

Figure 16: Representation of the horizontal distance. Perpendicular to Earth axis.

In order to make the system more robust, a third station should be deployed, so the triangulation can be done with 3 references, thus eliminating the variable of horizontal position that remains when applying 2 stations.
Adding a third station though, would increase notably the cost of the system.

3.7.4.3 Detection via radar

Radars have been used since the WWII for detection of airplanes, ships, vehicles, etc. This technology, consisting of beams of electromagnetic waves at very high frequency (400MHz-36GHz) emitted every few milliseconds allows detecting objects either in the surface or in the sky in a range of up to 3500 km. Measuring the time the beam travels to the object and back, in addition with some other parameters, the distance to that object is calculated.

This range nonetheless, would change according the frequency of beam emitting, also known as Pulse Repetition Frequency (PRF), the more pulses emitted, the lower the range, as seen in the following formula

$$R_{\max} = \frac{c_0 \cdot \mathrm{T}}{2} = \frac{c_0}{2 \cdot f_p}$$

where

c_0 = speed of light ($3 \cdot 10^8$ m/s)

f_p = Pulse Repetition Frequency

T = Pulse Repetition Time

Radars are normally used to detect mobile objects by using the Doppler effect. By doing so, it can remove static environment objects that would interfere in the tracking of the objectives, such as trees, mountains, buildings, etc. Radar is also commonly used to detect drones, utilizing the micro-Doppler generated by the propellers when rotating.

Since HAPS are quasi-stationary, they don't generate any Doppler effect, so this technique won't be useful in order to detect stationary objects.

Radar technology and detection via RF use similar technologies (the usage or electromagnetic waves), hence have some similitudes, such as availability to use during day and night, with any kind of meteorological phenomena, detect the distance to the object and a the usage of a similar equipment to process the information.

Radar however, have a challenge when trying to spot one specific type of HAPS, the airplane kind. As seen in *Figure 3*, aircraft must be as light as possible, in order to be able to fly electrically. Such characteristic makes that kind of HAPS to have a highly reduced Radar Cross-Section (RCS) and could be easily considered as a bird.

One of the main problems when detecting with a single RF station is that the UAS detected can be located in any direction of the 360º environment. Another solution for this problem is the usage of a radar. Radars scan the airspace sending short beam of radiofrequency every few microseconds and receiving the echos of the signal, once they impact in any object. Calculating the time traveled by the beam, the distance to the object is easily calculated.

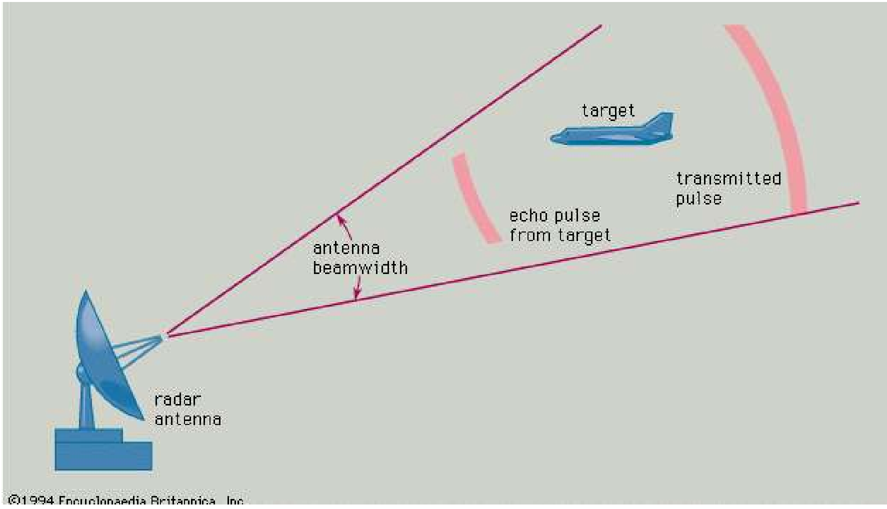

Figure 17: simple representation of a radar (Source: Encyclopedia Brittanica, Inc)

Using a radar as a secondary system would allow to once the RF system has detected a possible target, in a 360º, the radar would confirm this radiofrequency comes from an object (UAS, plane) and not from another source it could had interfered.

Combining the RF system and radar, we would have two main advantages:

- Using a radar as a primary system would detect any kind of aerial vehicle, but using it as a secondary, although it would still detect the same kind of objects, once a radiofrequency is detected at a given distance, the radar could filter that UAS from the rest of detected objects that don't transmit RF.

  Once detected, the radar would give the exact direction to the target, so the uncertainty of detection on the 360º would be erased.
- As UAS are quasistatic, aerial objects such as planes or helicopters that would operate in the same frequencies that we are detecting (for instance, aircraft transmitting its transponder mode S, used in the ADS-B system which operates at 1090 MHz) could be automatically filtered, as their speed is significantly greater than HAPS' one.

  This assumption couldn't be done properly only with RF as it couldn't disguise planes flying in Visual Flight Rules (VFR) or for instance aircraft doing performing a holding near an airport

Hence, combining both systems would allow to reduce the uncertainty from 3 dimensions (a volume) to 2 dimensions (an area), as well as giving a very high confidence that an object detected is a HAPS.

4. HAPS COMPETITION

Although HAPS is an unique concept, its function can be obtained via many different approaches. During the last years, different ideas have come and some companies have been working in prototypes that would compete with HAPS. Some examples are:

Space X, an airspace company founded in 2002 by Elon Musk has been experimenting with Starlink, a project that aims to set in LEO more than 10.000 small satellites that would bring broadband and low latency internet everywhere in the planet. This project has two big advantages respect many competitions. The first one is that they use their own rocket, the Falcon 9 in order to put 60 satellites per launch at a very low price, due to their reusability. The second one is the big marketing SpaceX and Elon Musk are doing regarding their rockets, being the first private company to send astronauts to space, sending a Tesla to Mars or broadcasting all their flights.

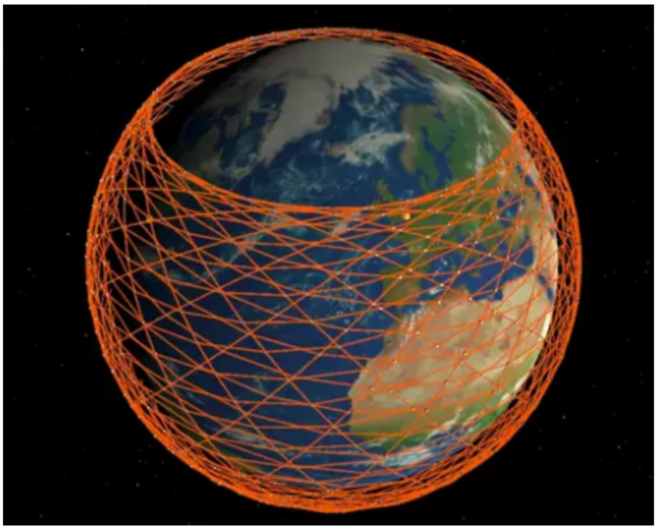

Figure 18: Starlink project aims to deploy over 10.000 satellites in LEO

There are another projects, similar to Starlink, such as OneWeb, which aims to send 600 satellites in orbit, giving internet to rural areas. The company was declared in bankrupt in 2020, possibly due to their unability to compete with SpaceX.

Google has been experimenting with a concept of stationary balloon, named as Google Loon. After almost a decade of development and breaking some records, such as being more than 300 days in space, the company have been shut down recently, stating "The road to commercial viability has proven much longer and riskier than hoped. The availability of the internet increased from 75% to 93% in the last 10 years in the area without stable connection."

Figure 19: Google Loon

5. CONCLUSIONS AND DISCUSSION

Although research about 5G and 6G is being currently carried out using HAPS, it is still unclear whether HAPS would become a big actor in telecommunications in the next years as countries start adopting 5G and IoT gains popularity or will just stay as a theoretical idea due to the rise of companies such as SpaceX that could overshadow HAPS. However they could be a good candidate to cover the areas that Starlink leaves uncovered, such as the poles, as well as used as a back up system in some areas.

In such case, as popularity of HAPS might increase, new ways of using this technology will arise and while some would be beneficial for society, criminal usage will start to show up, as it already happened with drones in the last decade, becoming a powerful weapon in the wrong hands. It is crucial to start developing systems to detect HAPS before they become popular so national security can be a step ahead of criminals.

During this project, we have explored the main considerations that will have to be taken in account in the further development of any system based on radiofrequency and/or radar technology. A complete detection system was not presented as it would take deeper research, knowledge and time, as well as it would only work for HAPS that are not invisible to radio frequency and radar detection (frequency hopping, minuscule RCS, etc), which isn’t realistic.
For that reason, further research must be carried out on detecting these UAS in the near future.

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APPENDICES

Appendix A, additional information

Specifications			
Electrical			
Frequency Range	Gain, typ.	Optimum Ground Plane Size	VSWR
138-174 MHz	3dBi	400x400 mm, 15.7"x15.7" (MG-400)	1.5:1 typ. (3:1 max)
380-450 MHz	4dBi	370x370 mm, 14.56"x14.56" (MG-370)	1.5:1 typ. (2.5:1 max)
450-512 MHz	5dBi	165x165 mm, 6.5"x6.5" (MG-165)	1.5:1 typ. (2.8:1 max)
698-746 MHz	6dBi	165x165 mm, 6.5"x6.5" (MG-165)	1.5:1 typ. (2.5:1 max)
746-806 MHz	7dBi	165x165 mm, 6.5"x6.5" (MG-165)	1.5:1 typ. (2.5:1 max)
806-960 MHz	7dBi	165x165 mm, 6.5"x6.5" (MG-165)	1.7:1 typ. (2.5:1 max)
1200-2700 MHz	8dBi	Not Required	1.3:1 typ. (2.0:1 max)
3300-3800 MHz	10dBi	Not Required	1.3:1 typ. (1.7:1 max)
4100-6000 MHz	11dBi	Not Required	1.5:1 typ. (2.0:1 max)
Polarization	Linear ,Vertical		
Pattern	OMNI Directional		
PIM, 3rd order, 2X20W	<-155 dBc		
Input Power, max	50 Watts		
Input Impedance	50 Ohm		

Table A.1:Specifications of the antenna Mars 138

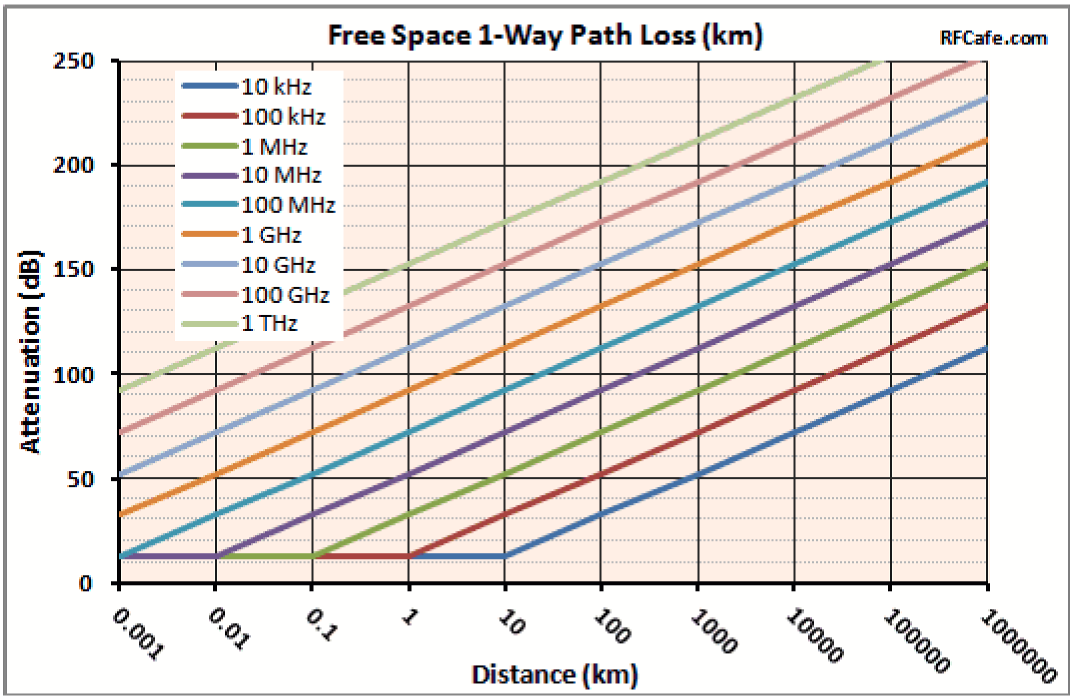

Figure A.1: Free-Space loss against frequency and distance