

About antenna

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1.Abstract

The CanSat competition involves lot of knowledge in many technical fields.

Electronic, soldering and microcontroller programming are difficulties usually overcome by the teams.

Communication between CanSat and the base station is a more sensitive area because it implies radio communication and antenna design.

Thanks to nowadays tech companies, the radio module like RFM69 can handle the very complex tasks of sending numeric data reliably from one point to the other through the air.

However, radio stuff involves a particular area of expertise which is the antenna design.

Antenna design WILL make the difference between successful or disastrous communication.

Contacting radio amateur club is certainly the best way to leverage that difficulty.

Otherwise this document is another way to find approved and tested antenna setup for the CanSat project.

A properly designed set of antennas (the CanSat and base station) did immediately demonstrate promising results. The initial setup tested in this document did send data over 2.2 Km, distance where the test was prematurely suspended.

2.Warning: avoids shortcut!

The temptation is great to jump directly to the technical information for building your antennas.

This document collects the information and steps taken to create and validate the antenna design. It is the learning curve followed by the author. It contains so much of “those little things” to know to avoid pitfalls.

The reader is strongly encouraged to follow the same learning steps as this will allow you to accumulate the adequate knowledge to validate the build of your antennas.

3.The «minimum power lost » game

Communicates via radio implies to send electromagnetic wave to the air. By essence, The emission of wave by using the air as conductor is not very efficient because the air is a very bad conductor (compare to copper wires).

Anyway **this is working if the power lost are properly managed.**

According to maker industries, a 100mW RFM69 module can transmit data over 1 to 2 Km.

According to radio amateur, 100mW is enough for a transmission over 4 to 5 Km with appropriate antenna set.

3.1.Where power is lost?

Getting the radio wave from the emitter to the receiver is literally playing the game of “minimum power lost”.

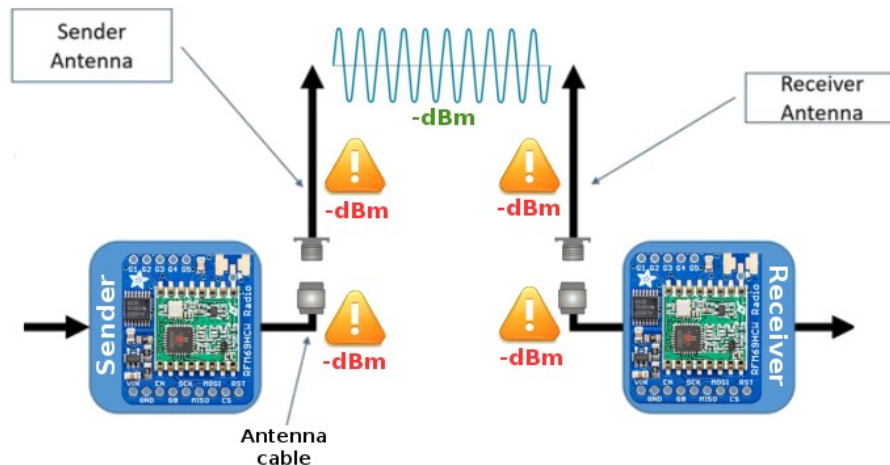


Fig 1: Where radio power is lost

As draw on figure 1, the power lost occurs:

- In the air
- In the antenna
- In cable and connectors

It is not possible to act over the air power lost. However, the power lost in cables, connectors and antenna can be reduced to the minimum with appropriate material.

The choice of an appropriate antenna may even results in a gain of power (a positive gain). The directional Yagi antenna is a great way to achieve it.

3.2.What transmission power for Cansat?

According to maker industries, a RFM69 module can transmit data over 1 to 2 Km.

According to radio amateur, 100mW is enough for a transmission over 4 to 5 Km with appropriate antenna set.

Our initial antenna set design confirm communication over 2 km (we didn't anticipate further distance for testing).

Therefore a radio power of 100mW (+20dBm) is more than enough to transmit CanSat data.

3.3.dBm and gain

dBm is a unit used for power measurement over a logarithmic scale. dBm use the mW (milliWatt) as base unit. 0 dBm = 1mW. **The dBm unit is a great way to have a perception of power.**

The value 0 dBm = 1mW while 20 dBm is 100mW and 30 dBm is 1000mW (1W). There is a straightforward relation between *dBm decade values* and the number of zero appearing in the mW power.

The figure 1 shows the corresponding power value (mW) of each dBm entry.

dBm	mW	dBm	mW	dBm	mW	dBm	mW
0	1.0	10	10	20	100	-1	0.8
1	1.3	11	13	21	128	-5	0.3
2	1.6	12	16	22	160	-10	0.1
3	2.0	13	20	23	200	-15	0.03
4	2.5	14	25	24	250	-20	0.01
5	3.2	15	32	25	320	-25	0.003
6	4.0	16	40	26	400	-30	0.001
7	5.0	17	50	27	500	-40	0.0001
8	6.0	18	64	28	640	-50	0.00001

Fig 1: dBm to mW conversion (source: fibermall.com)

A gain of power is expressed with positive gain (+x dB) whereas power Lost is expressed with negative gain (-y dB).

Example 1:

With a starting value of +20 dBm (100mW); IF the power falls to 0dBm (1mW) THEN we had a lost 20 dBm MEANING that the power value was divided by 100. That lost is also noted -20dB (dB having no unit).

The calculus is simple addition:

Output Power = Input Power + Gain (dB)
 Output Power = 20 dBm + (- 20dB) = 0 dBm
 Output Power = 1 mW

Example 2:

This second example starts at -10 dBm (so 0.1W); IF an amplifier bring a gain of +30 dB THEN final power is +20 dBm (100mW) MEANING that the power value was multiplied by 1000.

The calculus is still a simple addition:

Output power = Input Power + Gain (dB)
 Output power = -10 dBm + (+30 dB) = +20 dBm
 Output power = 100mW

3.4. More power is not the solution

Let's consider the following scenario:

- The antenna was not tuned and cause a loss of -14 dB (realistic value).
- The poor quality of the uFl to SMA cable a loss of -3dB (realistic value)
- The worn antenna connector have the center pin corroded. This results in a loss of -6dB (roughly estimated).

From the +20 dBm (100mW) of the RFM69 module the emitter power is

Output Power = +20 dBm – 14 dB – 3 dB – 6 dB = +20 dBm – 23 dB

Output Power = -3 dBm (0,5 mW)

From the 100mW on the Radio Module only 0,5mW goes to the air. **The power is divide by 200.**

Without fixing the quality issues of the antenna, cable and connector the loss will stay identical. As a result, the CanSat should contains a 20W amplifier to recover the 100mW at antenna output ($20W/200=0,1W$). This is a very inefficient way to solve the issue because almost all the injected power will be lost and dissipated as heat!

The paragraph here upper demonstrate that adding more power on a defective antenna setup is not the right way to solve a communication issue.

Here the steps to follows in case of power loss is suspected:

1. Check the antenna with appropriate tool (Vector Network Analyser). Tune it as necessary.
2. Check the cable/connector used with the antenna for power loss (Vector Network Analyser).
3. Having a reference setup may be useful to check/compare the changes made on an antenna. Simple straight pole are great as initial setup.

By comparison, the same 20W transmission power was placed on Voyager 1 and we still received data deep space.



Fig 3: Voyager I use a 13W radio emitter

If Voyager 1 can cover 100 millions Km with 100mW in deep space, we should be able to cover a few Km on earth with the same power.

4.Main type of antenna

It exists so many type of antenna but some of them are of them are really fundamentals

- Monopole antenna
- Dipole antenna
- Yagi antenna

4.1.Monopole Antenna

Also named mono-core antenna, this antenna is made of a stem pointing to the sky and perpendicular to the ground.

The stem is the driven element.



Fig 4: monopole antenna

The most common monopole is the quarter-wavelength antenna ($\lambda/4$ antenna). It is the kind of antenna found on Wifi modem.

The stem can also be mounted perpendicular to an artificial ground plane. A process used to create the so called helicoidal antenna.

The monopole antenna is the base for many derivate antenna design (see [monopole antenna](#) on wikipedia).

Remark:

This booklet will calculate, assemble and tune a monopole antenna. That knowledge will later be used to create a dipole antenna.

4.2.Dipole Antenna

A dipole antenna commonly named half wavelenght antenna ($\lambda/2$ antenna).



Fig 5: example of dipole

The **dipole** is a **driven element** cut in half (each having $\lambda/4$ length). The ground is connected to one half of antenna while the core is connected to the second half.

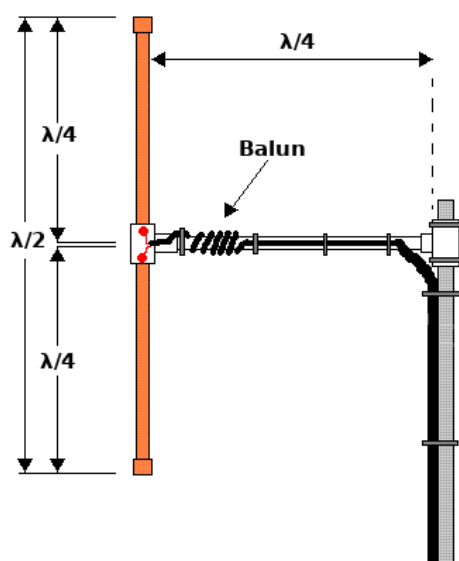


Fig 6: structure of a dipole

The dipole antenna can be used as base for a Yagi antenna (see [dipole antenna](#) on wikipedia).

Remark:

This booklet will calculate, assemble and tune a dipole antenna. That knowledge will later be used to create a Yagi antenna.

4.3.Yagi Antenna

The Yagi antenna uses a driven element, a reflector and several director elements to create a directional antenna.

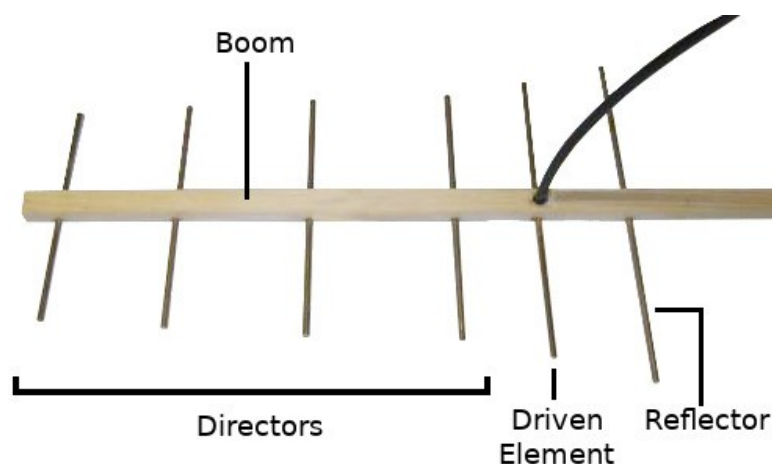


Fig 7: Yagi antenna

The driven element is designed to receive or send the radio wave. There is only one driven element on the Yagi.

The directors are placed at proper distance to capture the radio wave at the resonance frequency which will induce a current in the element, current that will create an electromagnetic field and re-emit the radio wave. Such way, the radio signal get reinforced in the direction of the driven element.

The reflector capture the radio wave and reflect it back to the driven element. once again, the aim is to reinforce the the strength of radio wave on the driven element.

The position and dimension of each element must be calculated carefully to obtain the expected signal reinforcement

Thank to its design, the Yagi antenna can offers a positive gains on the antenna. The value of the gain depends on the number of directors. More directors = Higher gain.

There driven element can be a dipole, folded pole, Jpole and other type of pole.

Remark:

This booklet will calculate, assemble and tune a dipole based Yagi antenna.

5.Radiation pattern

The radio pattern (ou antenna pattern) is the graphical representation of the antenna radiation strength for each direction. This also indicates the sensitivity of the antenna in reception mode.

It allows to determine the direction where the antenna is the loudest (or quietest).

The radiation pattern is a very valuable graphical information that can be simulated with software.

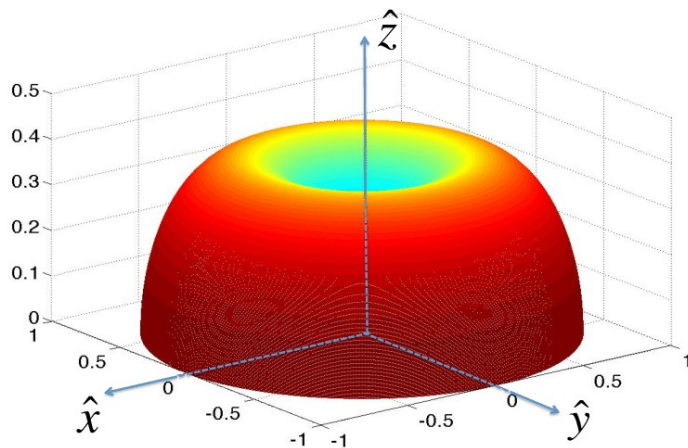


Fig 8a: monopole radiation (Source: internet)

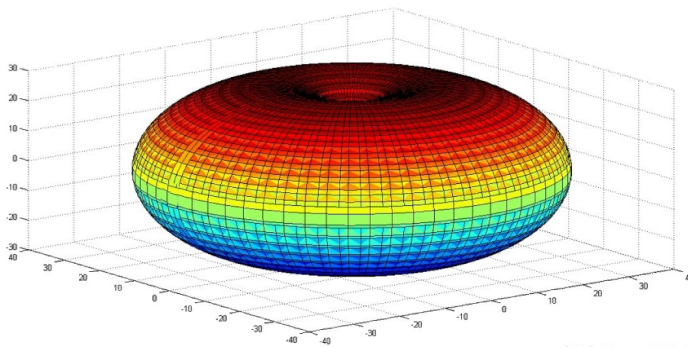


Fig 8b: vertical dipole radiation (Source: internet)

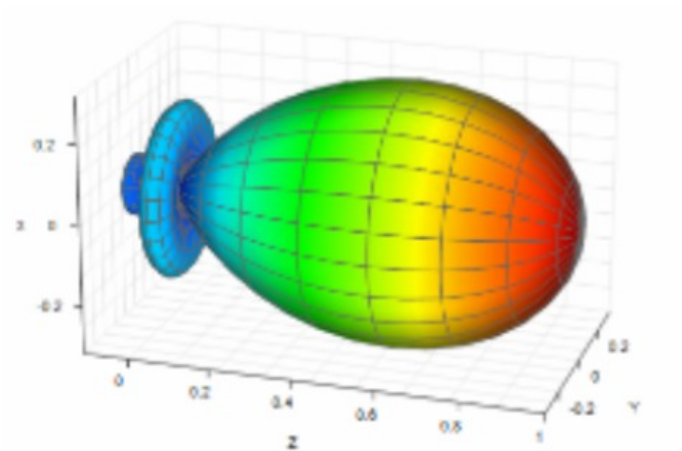


Fig 8c: Yagi antenna radiation (Source: internet)

6.Voltage and current distribution

It is interesting to know few electric facts about Voltage and Current distribution on an antenna. The most interesting antenna to study is the dipole as it is the main component of the Yagi antenna.

The antenna is designed to emit radio wave at a given frequency. This means that voltage and current continuously oscillate on the antenna (at the suited frequency).

The figure 9 shows the instantaneous capture of the voltage and current on the antenna.

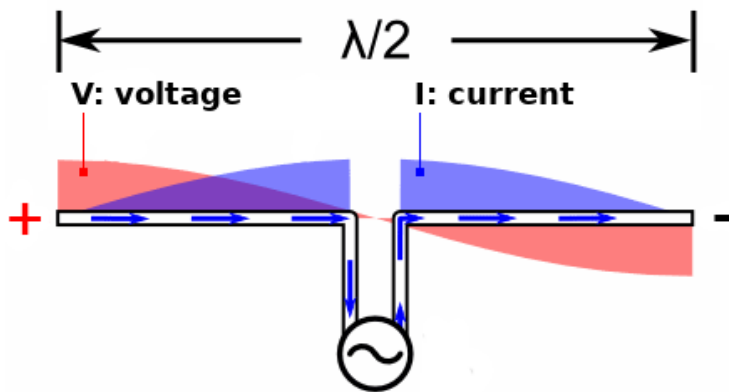


Fig 9: distribution of current and voltage into an antenna

The current is what matter the most in a antenna. In emitter mode, the current is feed at the center of the antenna, position were it will be at the maximum (since it is where ithe current is ejected).

Lets take the right pole: the current (in blue) will travel the antenna from the feed point up to the end of the pole. At the end of the pole the current can't escape so its value must be null. Note that resistance to the air

Now, the left pole: the current outgoing to the right pole must be equilibrated with a current entering from the left pole. The current is at the maximum at the feed point and null at the end of left pole.

As the resistance of each pole will be a linear increase from 0 Ohms (at the feed point) to a maximum at the end of the antenna pole. It is way the voltage increase to a maximum when travelling along the pole to the end.

Regarding the opposite pole, as the current flow in the opposite way, the voltage also increase the opposite way.

The [Dipole Antenna](#) wikipedia page shows a very nice animation that demonstrates how the electromagnetic radio wave do generates voltage and current in antenna (receiver mode).

7.ISM Band and regulation

ISM band stand for Industrial, Scientific and Medical band where it is used.

ISM band allows telecommunication without the need of a licence. Such band are usually not regulated but have constraints to avoids interferences between services.

ISM band are shared between service, good practice is to not generate perturbation to other service working over the same band.

7.1.433 MHz ISM Band

In Belgium, the maximum allowed radio power for devices operating in the 433 MHz frequency band is 10 milliwatts (10 mW) or +10 dBm.

The 433 MHz frequency band is also used by LPD433 (low power device 433 MHz) where it authorize licence-free voice communication in most of Europe (FM modulation, 25 Khz channel spacing, 10mW max). See [LPD433](#) on Wikipedia.

Note: Member of the UBA with a valid licence can increase their transmission power.

Sub-band (MHz)	Duty Cycle (per Hour)	Max Power	Remark
433.05 – 434.79	---	10mW	Norme EN55011
435.00 – 438.00	reserved	reserved	Amateur satellite band

Fig 10a: 433 MHz ISM Sub-band

RFM69 channels

Modules as the RFM69 can use packet radio to transmit data over the air. The figure 10b show the waterfall of an emission centred on 868 MHz (in this case). The waterfall reveals a channel of 60 KHz.

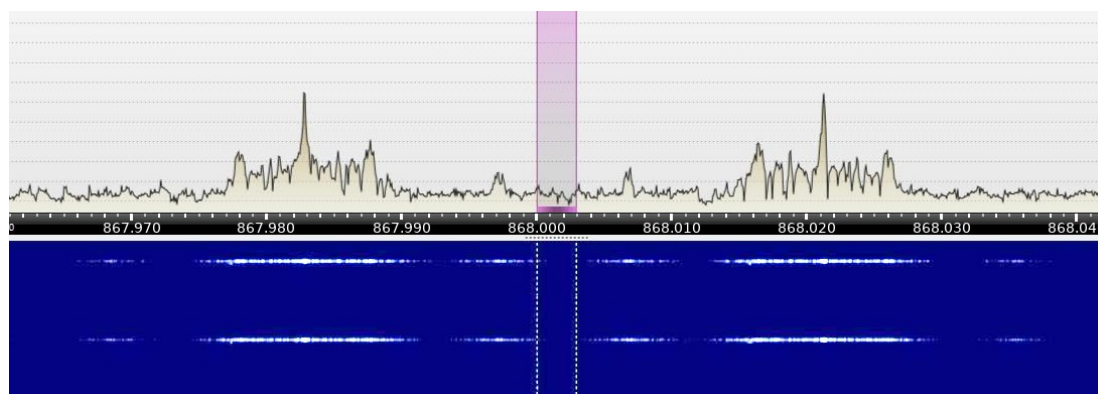


Fig 10b: RFM69 channel size

7.2.868 MHz ISM Band

The 868MHz band is a public bandwidth for **European Low Power Networks (LPWAN)** as Sigfox and LoRaWan global networks uses for communicating.

Basically, the 868Mhz band is going, from 865MHz to 870MHz and split in 6 different sub-bands where different rules applies.

This bandwidth is regulated by different norms like ERC-REC-70-3E in Europe (translated in national norms).

The 868Mhz band is going from 865MHz to 870MHz and **split in 6 different sub-bands** where different rules applies.

The rules are based on 2 restrictions:

- Transmission power:** it is the maximum power an emitter can use on the channel when it is communicating. 25mW (14dBm) is the usual power uses for communicating.

- The duty cycle:** it is defined as the maximum ratio of emitting time on the air per hour. Basically, 1% means you can speak 36s per hour, no more. Duty Cycle may vary from sub-band to sub-band.

Sub-band (MHz)	Duty Cycle (per Hour)	Max Power	Remark
865.0 – 868.0	1,0%	25mW	
868.0 – 868.6	1,0%	25mW	SigFox & Canaux Standards LoRaWan
868.7 – 869.2	0,1%	25mW	
868.3 – 868.4	---	10mW	
869.4 – 869.65	10,0%	500mW	LoRaWan downlink
869.7 – 870.0	1,0%	25mw	

Fig 10c: 868 MHz ISM Sub-band

The 865.0 MHz → 868.6 MHz is a large area to add LoRa or SigFox Channels even if it is limited to 25 mW / 1%. Notice that the frequency range is also used by RFID. SigFox defines 2000 channels of 100 Hz each (total of 200 KHz). LoraWan defines the first channel of 125 KHz (centered on 868.1). Message collision will occur!

The 868.0 MHz → 868.6 MHz contains the 3 standards LoRaWan channels (and 2000 Sigfox channels).

The 868.7 MHz → 869.2 MHz is a 25mW with restricted 0.1% duty cycle. The sub-band is suited for object emitting once a day. The risk of collision is really low and re-emitting the data with second collision is fairly low also. This band is used by objects that needs to preserve energy.

The 868.3 MHz → 868.4 MHz have no time restriction but very limited to 10mW. As the consequence, communication distance is shorter! This sub-band is suited for local communication between objects (located in the same area).

The 869.4 MHz → 869.65 MHz with 500 mW (10% duty cycle) is a good channel for gateway since it allows to send more powerful transmission to distant object (and still being over the noise floor when the message is received by the object). The larger duty cycle allow the gateway to communicate with a large quantity of objects. To resume, it allows LoRaWan objects to received data.

The 869.7 MHz → 870.0 MHz is used to deploy extra LoRaWan channels

LoRaWan & SigFox channels

It is also important to remind the spread of standard LPWAN channels on the 868 MHz band.

Sub-band slice (MHz)	Duty Cycle (per Hour)	Max Power	Remark	
868.0 – 868.1	1,0%	25mW	LoRaWan Std Channel	SigFox Channels
868.1 – 868.2	1,0%	25mW		
868.2 – 869.3	1,0%	25mW	LoRaWan Std Channel	
868.3 – 868.4	1.0%	25mW		
868.4 – 868.5	1,0%	25mW	LoRaWan Std Channel	
868.6 – 870.6	various Config.	various Config.		

Fig 11: LPWAN channels distribution

The LoRa Spreading Factor

The spreading factor (SF7 to SF12) is a crucial parameter that influence the data rate, receiver sensitivity, distance of communication and resistance to noise.

LoRa spread the signal by using the CSS (Chirp Spread Spectrum).

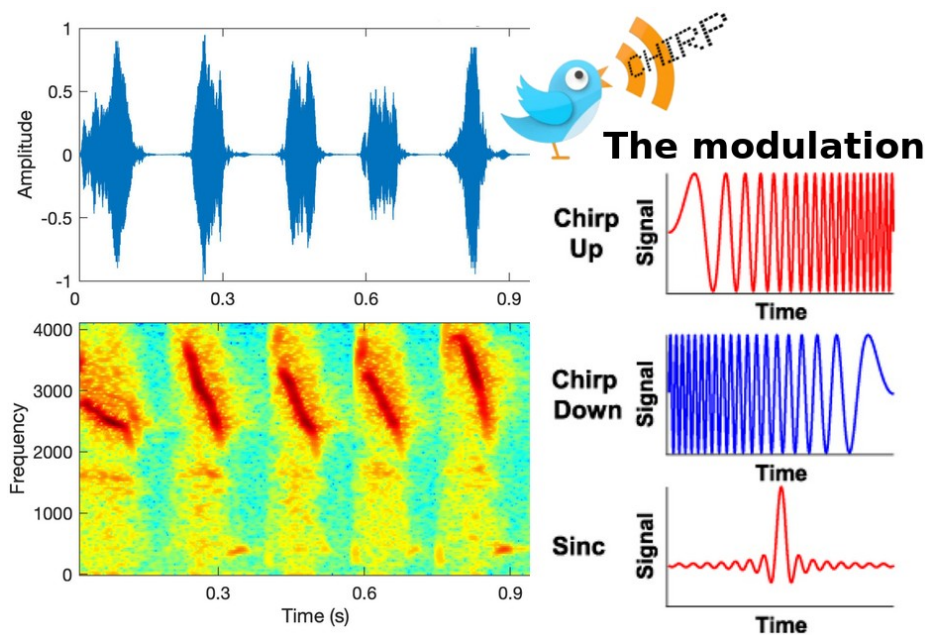


Fig 11: Chirp Modulation. Source: The Journal of Engineering (partial)

The spreading factor controls the speed of the chirps. Higher spreading factor means that chirps move slower. As a result, it will have larger usage of the spectrum.

Higher Spreading Factor will requires more time to send chirps, this would result in lower data rate (same amount of data will requires more time to transmit with SF12 and less time with SF7).

The main benefits of a higher Spread Factor is a better penetration through obstacle and ability to achieve larger communication distance. The signal is less sensitive to perturbation/small perturbation because it is technically stronger.

The pitfall of higher Spread Factor is its low data rate.

Resume:

- **Low SF:** Higher data rate, short range, more vulnerable to noise. Ideal for urban area.
- **High SF:** Lower data rate, wider range, good performance in noisy environment. Ideal for long distance sending like rural & farming environment.

Source: [All what you need to know about regulation on RF 868MHz for LPWAN](#)

7.3.Using LoRa with CanSat?

LoRa is known for its very long distance transmission and very low make it appealing for transmitting telemetric data. It is often seen as a solution by teams getting antenna build issue.

However, the all problems stays identical: the CanSat flies and the ground station must increase the chance to capture the signal. So proper antenna must still be designed and built.

The LoRa Modulation

The LoRa Modulation is also named “chirp” as metaphore of bird chirps able to pass over the surrounding ambiant noise. This is the reason why LoRa signal can be received at such a long distance.



20 – The Chirp modulation in action

As you may guess from the picture above, the bird's chirp can easily be eared and identified.

For this to work, the **noise level must stay as low as possible!** It is the raison why the LoRa regulation **limits emitting to 1% of the time** (36 seconds of intermittant transmission every hour).

It is tempting to ignore such restriction rule while performing CanSat launch. This however a fondumental error as many teams are competting in the air (and

agressively transmitting LoRa packet) and many teams on the floor are testing their LoRa setup (also transmitting LoRa packet).

This would results into a quite higher noise level... with its negative consequences regarding the reception of data at the ground station.



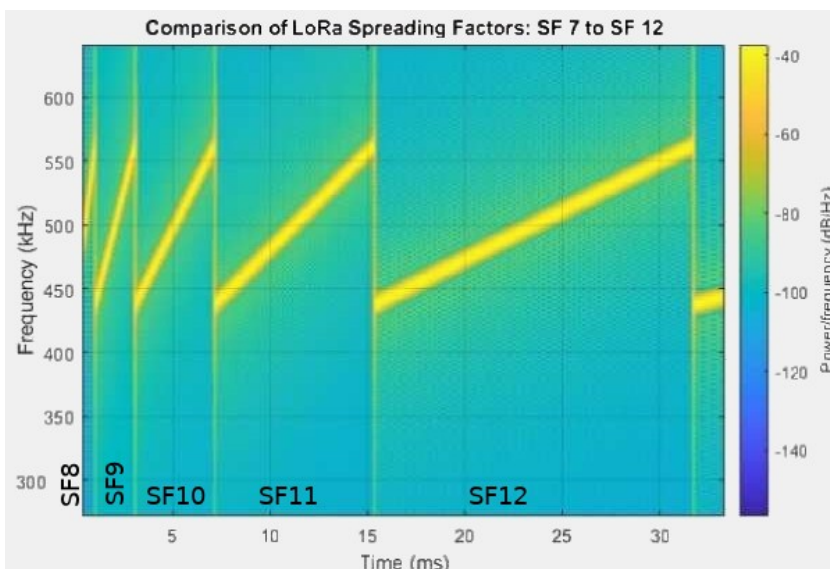
21 – Noise Level Increase because of unrespectful LoRa transmission

This situation also disturbs/destroy regular LoRa transmission on the 20 Km around! RF world relies on respect of the rules and this should applies in this case.

Spreading factor

The Spreading Factor (SF) immediately determine the time required to emit the Chirp. Higher is the spreading factor, slower is the frequency shift while emitting the Chirp.

Higher SF will results into a transmission more immune to noise, slower data rate and higher transmission distance (as the signal is more stable).



22 – comparison of various spreading factor

Notice that higher spreading factor is also more sensitive to collision (as it need more time to be transmitted).

In a heavy LoRa load environment higher spreading factor will make the best to safely transmit the data. However it will also participate to the noise level increase.

Conclusion

In the author's view, LoRa is not an appropriate choice for the CanSat contest.

LoRa is not designed for high data rate or heavy load.

Diverting LoRa from its intended use will not solve antenna design/built issues (since this must still be done properly with LoRa modulation).

Moreover, this will also creates other issues (noise level increase) and disturb the regular users of the network.

7.4.Belgian rules, regulation, transmission power

CanSat competition must comply with RF emissions law. Those are described in the reference documents (see below).

In the 433Mhz range:

- Emitter antenna must be OmniDirectionnal (vertical element). OmniDirectionnal emitting identical power in all the direction)
- Receiver antenna can be directional (like Yagi antenna)
- Transmitted power is limited to 10 dBm (10mW, no exception)

The following MicroPython code excerpt is in accordance with the regulation.

```
FREQ          = 433.1

spi = SPI(0, miso=Pin(4), mosi=Pin(7), sck=Pin(6), baudrate=50000,
polarity=0, phase=0, firstbit=SPI.MSB)
nss = Pin( 5, Pin.OUT, value=True )
rst = Pin( 3, Pin.OUT, value=False )

rfm = RFM69( spi=spi, nss=nss, reset=rst )
rfm.frequency_mhz = FREQ
# Possible values:
#  -2 dBm = 630uW
#   0 dBm = 1mw
#   3 dBm = 2mW
#   5 dBm = 3mW
#   7 dBm = 5mW
#  10 dBm = 10mW
#  13 dBm = 20mW
#  15 dBm = 31mW
#  17 dBm = 50mW
#  20 dBm = 100mW
rfm.tx_power = 10 # 10 dBm = 10mW Maximum Allowed!
```

Reference documents

<https://old.uba.be/en/belgian-rules-and-regulations>

<https://www.ibpt.be/operateurs/plan-des-frequences>

8.SWR : Standing Wave that kills the emitter



This point is crucial and should not be ignored

When the antenna have exactly the right length then all the power is transmitted from the antenna to the air otherwise a part of the wavelength is reflected back to the emitter.

The part of the reflected power to the emitter depends on the right adaptation of cable and antenna.

The reflected waveform will interfere with the waveform still produced by the emitter. This will results in a stationary waveform with maxima and minima. Such stationary waveform may represent a small or medium part of power. In worst case, none of the power is emitted to the air causing heat and possibly damage the emitter.

The SWR (Standing Wave Ratio) is a great way to estimate the part of the power that is reflected to the emitter.

SWR meter (also named ROS meter) are used by Radio Amateur to estimate the power transmitted to the air vs power lost/reflected.

SWR	Description
1.0 → 1.5	The ideal range! The SWR value under 1.5 is really great! Getting under 1.5 (closer of 1) is possible but you may consider additional tuning, other equipment and different mounting location. Dropping under 1.5 will not increase the performance in significantly.
1.5 → 1.9	Provide an adequate/acceptable performance. It's sometime difficult to get under SWR = 1.5 usually due to the installation. This SWR range often means that the tuned antenna is mounted in a less-than-ideal location. To troubleshoot, search for paper dealing about "problematic antenna mounting locations". Going from 2.0 down to 1.5 will offer noticeable improvement.
2.0 → 2.4	While not good, it won't damage the radio for casual use. It's by no means a good tuning job, but will function until it gets improved (what should absolutely be done). To troubleshoot, you'll likely need to move the mounting location and/or use a more suitable antenna.
2.5 → 2.9	DO NOT OPERATE RADIO IN THIS RANGE. The antenna have decreased performance and may damage the transceiver in case of long period (or frequent) transmitting. To solve: change your location and/or antenna.

3.0+	DO NOT OPERATE RADIO IN THIS RANGE. NEVER transmit with a SWR levels above 3.0, this will probably damage the radio. This is the result of a poor ground or incorrectly assembled material (faulty coax, faulty antenna, device not properly attached).
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By chance, we can also estimate the SWR of an antenna under construction with a tool named Vectorial Network Analyser (like NanoVNA).

The figure 12 show the NanoVNA displaying the LOGMAX measurements on a full frequency range of an Yagi antenna. Values are displayed as SWR format (thanks to a Display option). The left axis shows SWR value from 1 to 10 (from down to top).

As seen on the chart, several point falls under 2 meaning that we got acceptable/good performance for those frequencies where most of the power emitted to the air. The cursor placed on the first "pit" indicate a SWR of 1,42 at 390 MHz (result must be refined).

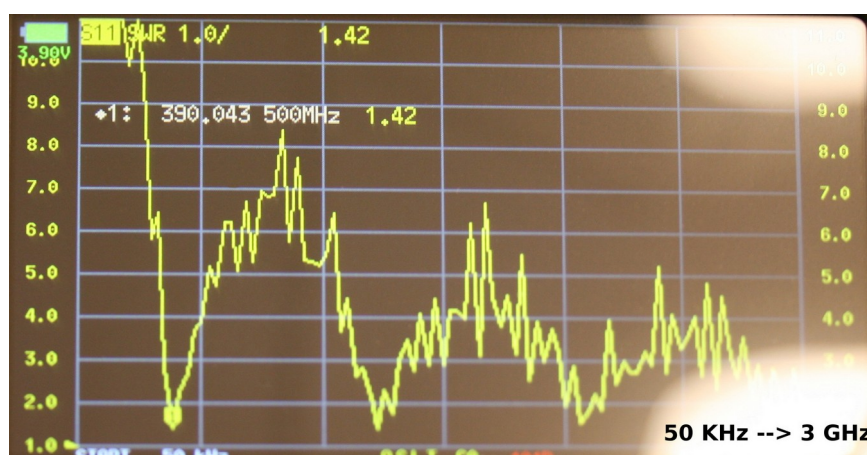


Fig 12: NanvNA LOGMAX measurement (display as SWR chart)

LOGMAX measurement

Tools like Vectorial Network Analyser usually displays an initial LOGMAX measurement. This measurement can easily be converted to SWR thanks to a display option.

LOGMAX (S11) sends waveform into the antenna over a range of frequency (50 KHz to 3 GHz depending on NanoVNA model) and measure the reflected power. The resulting chart is displayed in dB where dropping value indicates frequencies having the best transmission to the air.

The figure 13 show the LOGMAX from 50 KHz to 3 GHz for a simple pole antenna. Accordingly to the chart, several value drops are visible.

The cursor place over the most important one displaying a drop of -23,20 dB at 300 MHz meaning that almost all the power was sent to the air. It is a 300 MHz antenna (Notice that frequency must be refine).



Fig 13: NanoVNA LOGMAX chart of a single pole antenna.

The LOGMAX chart is a good way to identify the best frequency for an antenna.

The value at desired frequency should be at least below -10 dB. Below -15 dB is good antenna whereas -20dB (and below) are great since almost nothing seems reflected to the emitter.