A Guide to Radio

Introduction

Radio contains elements of both science and "black art". The science allows you to determine what should happen to a radio signal over a predictable radio path. The black art explains what really happens because no radio path is wholly predictable. This section of the website explains the science of predictable radio paths and introduces some of the factors which can be used to take account of the lack of predictability.

This section does not cover the design or building equipment as most rocketry is based on commercial equipment. I would refer anyone thinking of building their own transmitters, receivers or antennae to the excellent range of publications by the Radio Society of Great Britain (RSGB) or the American Radio Relay League (ARRL). The aim is to link the specifications of equipment, such as transmitted power, receiver sensitivity, antenna gain, to be used to generate the maximum range, antenna pointing accuracy, and other metrics which will allow the system performance to be estimated.

Radio calculations require a working knowledge of decibels. This site contains a short primer on logarithms and decibels for those who wish to re-acquaint themselves with decibels.

General Principles

Radio links from a rocket can be used for many purposes:

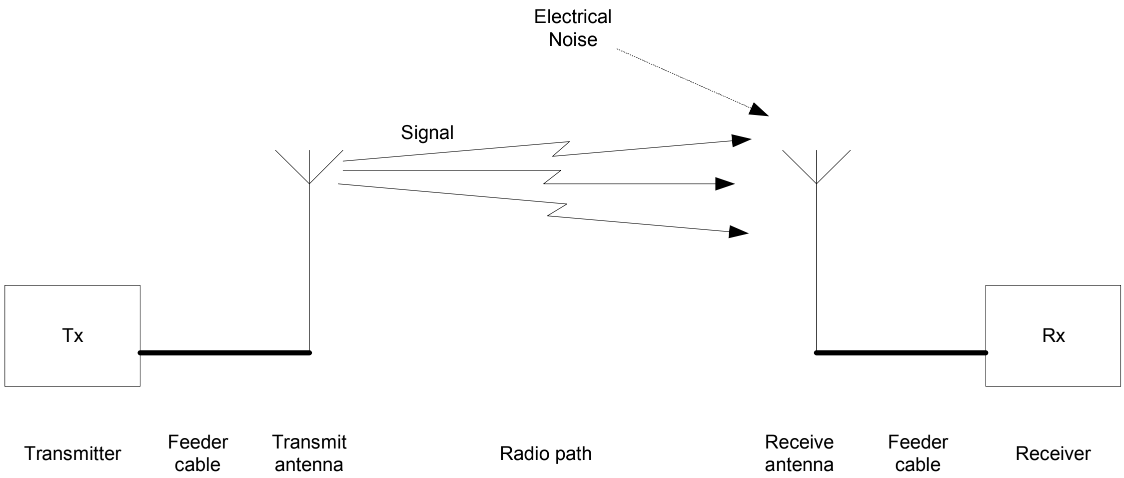
- Telemetry, used to carry information about the rocket or payload to the ground in real time.
- Tracking, to locate the position of the rocket in the air
- Location of the rocket after it has landed
- Payload data, for example live video cameras

The majority of electronic devices in model rocketry are commercial devices which need to be integrated and powered. The instructions for the use of these devices are normally quite adequate to bolt together the bits and make them work in the workshop. It is more difficult to predict how the radio system will perform between a rocket in flight and the ground, when the received signal is much weaker. Why is it weaker? Here are a few considerations:

- The power of the signal decreases with the square of the distance: double the distance you get a quarter of the signal, treble it and you get an eighth of the signal.
- The receiver antenna is often directional. If you're not pointing directly at the rocket you'll lose some signal.
- Antennae on rockets are generally very inefficient and radiate power in all sorts of unwanted directions.
- The rocket materials may absorb some of the transmitted signal, so that power will not get radiated (this becomes more critical as you increase in frequency)
- The polarization of the signal will vary as the rocket's orientation changes. This can affect the signal strength very significantly (try receiving horizontally polarized TV signals on a vertically polarized antenna).
- The receiver will not only pick up the signal, but also receives noise from the environment. If there is too much noise the receiver won't be able to segregate the signal from the noise.

These, and other, effects can be calculated or estimated individually. The results of each calculation can be used to estimate the overall system performance in a LINK BUDGET. This section of the website concerns itself with the calculation of link budgets.

The components of a typical radio system are:



Radio Path Components

Each of the components has properties which affect the performance of the whole system. These properties can be summarised as follows:

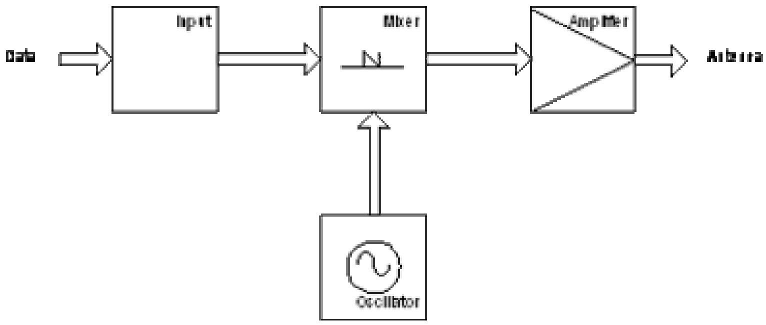
Transmitter	Puts power into the feeder. Normally this is measured in Watts, although a more useful unit is the dB relative to one watt dBW (0 dBW = 1 Watt) or one milliwatt dBm (0 dBm = 1 mW)
Transmit feeder	Has a loss in dB per meter. This means that the signal power is attenuated before reaching the aerial so less power is radiated.
Aerial	Has gain in dBi, and beamwidth in degrees, which are related. Efficiency of power transfer between feeder and radiated power is typically 50%. The output signal from the aerial is the input signal times the gain. The beamwidth dictates the accuracy with which the aerial must be aligned, and also its tolerance of movement (wind etc.).
Radio Path	The signal losses in free space increase with distance and frequency. There are many other factors, such as meteorological effects and path geometry, which affect the propagation of the radio signal through the atmosphere.
Receive Aerial	Same properties of gain and efficiency as transmit aerial. Sky noise is treated as being an equivalent temperature presented at the aerial output.

Receive feeder	Receive feeder has loss in dB/m. The longer the feeder the weaker the signal.
Receiver	The receiver will have a stated sensitivity, usually a power level in dBm below which the signal will be too weak to be received reliably.

Transmitters

The purpose of the transmitter is to take the baseband signal, convert it efficiently to a radio frequency, amplify it and present it to the aerial. We can view a transmitter as 4 blocks:

- An interface stage, which sorts out the voltage and timing requirements of the input signal
- A modulation stage, which turns the input into a radio signal
- An oscillator/mixer stage which changes the frequency of the radio signal
- An amplifier stage, which boosts the power of the radio signal



Transmitter Block Diagram

Receivers

The function of the receiver is to take the weak received signal, amplify it and demodulate it. It must do this reliably in the presence of noise, fading and other unwanted effects.

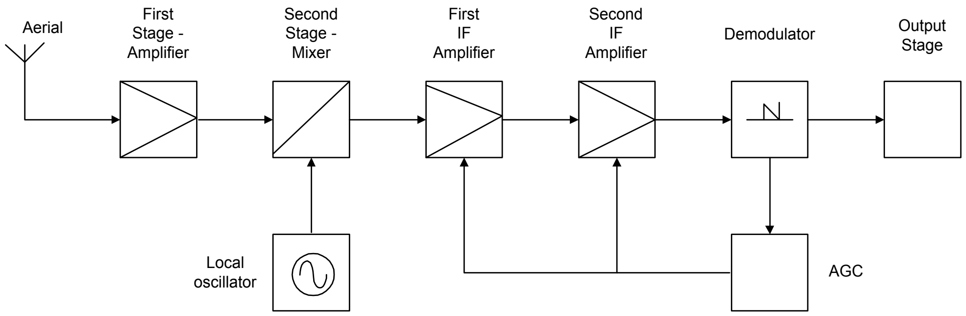
Receivers are, generally, more complex than transmitters as they have to perform more functions. One of the more complex functions of a receiver is to cope with a range of signal levels without degrading the signal quality. For example, the signal received from a tranmsmitter which is 100m from the receiver (a rocket on the pad) will be much stronger than a signal from an identical transmitter at 2000m (rocket at 6000 ft). In this case the signal power will reduce to about $1/3000^{th}$ of the original signal.

The receiver copes with this by detecting the signal level and controlling how much the signal is amplified. This technique, called automatic gain control (AGC), is best implemented at one frequency so the receiver will change all radio signals to a common “intermediate frequency” (IF) at which most of the amplification and signal processing takes place.

A typical receiver has several stages:

- The first stage amplifies the weak radio signal.

- The second stage is an oscillator and mixer which convert the signal to the intermediate frequency
- There are usually two or three stages of amplification at IF
- The demodulator stage recovers the signal from the noise (to the best of its ability) and controls the AGC system; is the signal is too weak it increases amplification until an adequate signal is obtained (sometimes the signal is too weak).
- Finally, the output stage presents the recovered signal in a form that the end system can use, maybe audio, video or data for a PC.



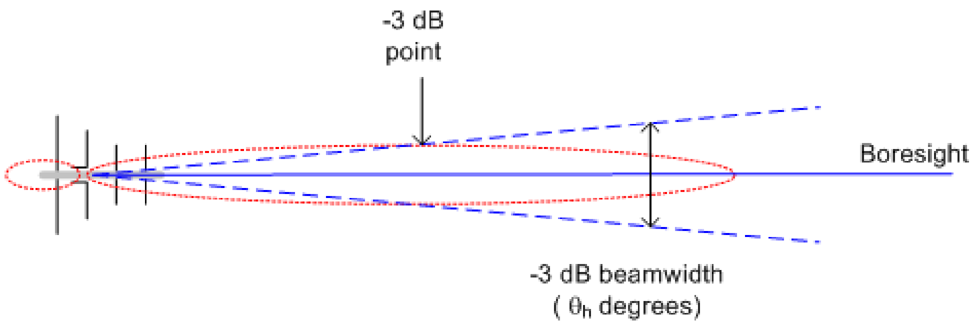
Radio Block diagram

Antennae

The purpose of a transmit antenna is to convert the currents in a cable to E-M waves radiated through "free space". A receive antenna reverses this process, converting E-M waves to currents. Almost all antenna types behave identically whether being used for transmitting or receiving E-M waves; this is known as reciprocity.

A perfect form of antenna, known as an isotropic radiator, will radiate its signals equally in all directions. The isotropic radiator has a fundamental problem from an engineering perspective: it is impossible to make on in practice. Nevertheless, the isotropic radiator has one use: it provides a theoretical benchmark against which all other antenna can be compared.

One such comparison is gain, which is the apparent increase in signal power caused by the focussing of the beam in one preferred direction. We generally compare the gain of an antenna to an isotropic radiator and quote this value in dBi. Sometimes gain is quoted in dB with respect to a dipole (dBd), however manufacturers generally don't use this as a dipole has a gain of 2.1 dBi, thus the value for gain in the sales literature is smaller and less impressive in dBd than dBi.

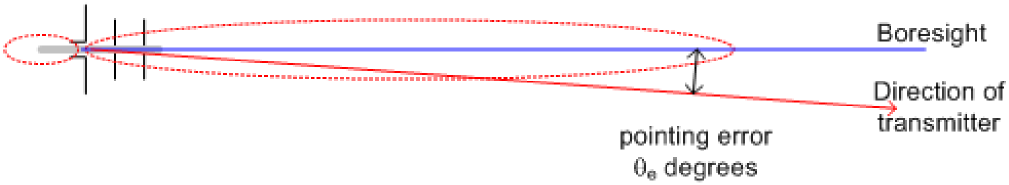


It can be seen that the gain of a directional antenna decreases as we move a small angle off the boresight. The gain of the antenna is achieved at the cost of reducing the width of the main lobe. We define the edge of the beam as being the direction in which the power has reduced to half the value at the boresight. Halving the power is akin to a loss of -3dB in power, so this definition of beamwidth is generally called the **-3dB beamwidth**.

An approximate equation for calculating the -3 dB beamwidth of an antenna was estimated by Kraus:

$$\theta_h \approx \frac{228\pi}{\sqrt{G}} \text{ degrees} \quad \text{.. equation 1}$$

The value of G is the gain as a number, not in dBi. Beamwidth is important for pointing dishes. The narrower the beamwidth the more accurately the dish needs to be pointed. This can give problems when trying to point a high gain (narrow beamwidth) antenna at a distant rocket.



For small pointing errors, defined as angles which are less than half the -3dB beamwidth, the pointing loss can be approximated to:

$$L_p \approx 12\left(\frac{\theta_e}{\theta_h}\right)^2 \text{ dB} \quad \text{..Equation 2}$$

Note that this calculation gives its answer in dB.

Radio Path

In a perfect environment, such as interplanetary space, the only losses are due to the spreading of the signal. The received signal power on a perfect radio path can be calculated from the Friis power equation:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi r)}$$

where P_r is the received power, P_t the transmitted power, G_t and G_r the gain of the transmit and receive aerials, λ the wavelength and r the distance between aerials, all distances being in metres. The received signal power clearly decreases with the square of the distance, and increase as the gain of the aerials increases. It also increases as wavelength increases, (or conversely the received signal strength decrease as frequency increases).

We can rearrange the Friis equation to show the how many Watts of received power we get for every watt of transmitted power. We call this the "free space loss equation", as it shows the loss in power of the signal is "free space", which is another term for a perfect environment.

$$L_{fs} = \frac{P_r}{P_t} = \frac{G_t G_r \lambda^2}{(4\pi r)}$$

Where L_{fs} is the amount of loss in free space. A more convenient form of the free space loss equation is the logarithmic form, where the loss is expressed in decibels (dB):

$$L_{fs} = 32.4 + 20\log_{10} f + 20\log_{10} d \quad \text{dB} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{equation 3}$$

Note that the frequency is in MHz, and the distance in Km. The Friis equation holds true on all radio paths. Additional effects due to imperfections in the path, for example when the path goes through an atmosphere, can be factored in as additional losses. In the earth's atmosphere it is common to account for losses due to rain (L_{rain}) and the effects of Oxygen (L_{O2}) and Water vapour (L_{H2O}). These generally don't affect model rockets as the frequencies concerned are not available to rocketeers, furthermore we tend not to fly in the rain!

The Friis and free space equations makes the important assumptions that the aerials are correctly pointed. There are additional pointing losses due to the changing attitude of the rocket and the pointing accuracy of the antenna on the ground. The rocket antenna is particularly difficult to model; rather than try to work out the pointing loss I tend to assume it is omnidirectional with very low gain (-3dBi). The pointing loss of the transmit antenna can be estimated using equation 1.

While the rocket is in flight the path is not obstructed by vegetation, but may be obstructed after landing. Foliage losses can be a real pain to calculate. NASA have done extensive modelling of foliage losses of signals from satellites, and concluded that the amount of loss depends on a load of factors including:

- Frequency
- vegetation type (grass/crops, scrub, coniferous forest, broad leafed forest etc)
- season (amount of leaf cover, moisture content of plants)
- terrain profile (flat, rolling, irregular, hilly, mountainous)

For practical purposes it is assumed that most rocket flying takes place in flat terrain with grass/crops and scrub. Moisture content is viewed as moderate. This gives the following approximate losses in dB for each meter of foliage along the path:

Frequency (MHz)	**Loss (dB/m)**
200	0.05
500	0.1
1000	0.2
2000	0.3
3000	0.4

Cables

Feeder loss characteristics of a cable are usually quoted in terms of frequency and loss/100m in dB. The data is available from the manufacturer or, in the case of common feeder types, it is published in data books. If we have a cable of length *l* meters, and it has a loss of *x* dB/m, then the total cable loss is simply:

$$L_c = lx$$ …………………………………………………………………. equation 4

Link Budget

To calculate the performance of the link we build a link budget. Typically these are laid out in a table, and look something like:

Parameter	**Symbol**	**Value**	**Notes**
Transmit power (dBm)	P_T	+ 10.0	From Tx spec
Transmit cable loss (dB)	L_{CTx}	- 0.5	equation 4
Transmit antenna gain (dBi)	G_{Tx}	- 3.0	Assume -3 dBi
Path Loss(dB)	L_{FS}	- 85.2	equation 3
Other path losses: (dB)			Rain, atmospheric gases, foliage as required
Receive antenna pointing loss (dB)	L_P	- 0.7	equation 2
Receive cable loss (dB)	L_{CRx}	- 0.6	equation 4
Signal presented at receiver input (dBm)	P_R	- 80.0	Sum of all the above numbers
Required signal at the receiver (dBm)	P_{Req}	- 90.0	From the receiver spec.
Margin		+ 10.0	the difference between required and received signals.

Worked Example

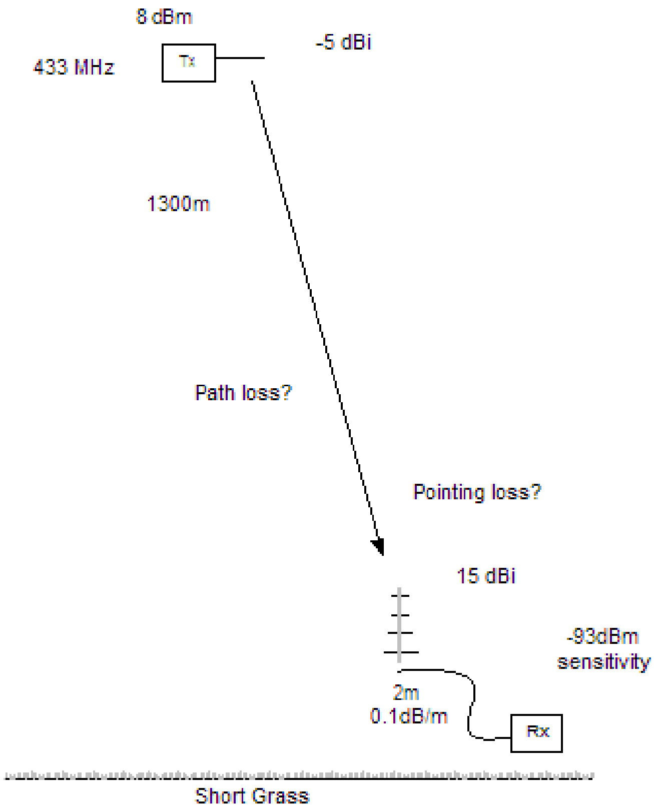
A rocket flies to 1300 m altitude from a short grass field. It's transmitting a telemetry signal to the ground, where it is received using a manually pointed antenna with 15 dBi gain; the tracker reckons he can point to within 5 degrees. The rocket is transmitting 8 mW (9dBm) at 433 MHz using a cheap wire antenna with – 5 dBi gain. The antenna is wired directly to the transmitter so there is no cable loss.

The receiver has a stated sensitivity of -93 dBm, and is wired to the antenna using 2m of cable with a loss of 0.1dB/m at 433 MHz. The rocket appears to land in a 300m diameter patch of scrub.

Q1. can the signal be received all the way to apogee.

Q2. Will there be enough signal to locate the rocket from the edge of the scrub?

A1. First, draw the problem.



We know most of the data to assemble a link budget. We need to work out the path loss and pointing loss.

Frequency is 433 MHz, distance = 1.3 km (1300m) if we put the receiver underneath the expected apogee.

Path loss = 32.4 + 20 log (433) + 20 log (1.3) = 87.4 dB

Pointing loss requires that we know the -3 dB beamwidth θ_h to substitute this into equation 2. We know the gain (in dBi) so we can convert this into a ratio and substitute it into equation 1 to get the beamwidth.

Gain = 15 dBi, which is $10^{15/10}$ as a ratio = 31.6

$$\theta_h \approx \frac{228\pi}{\sqrt{G}} = \frac{228\pi}{\sqrt{31.6}}$$

θ_h = 127 degrees (quite a wide beam)

As the tracker can point within 5 degrees:

$$L_p \approx 12\left(\frac{\theta_e}{\theta_h}\right)^2 = 12\left(\frac{5}{127}\right)^2$$

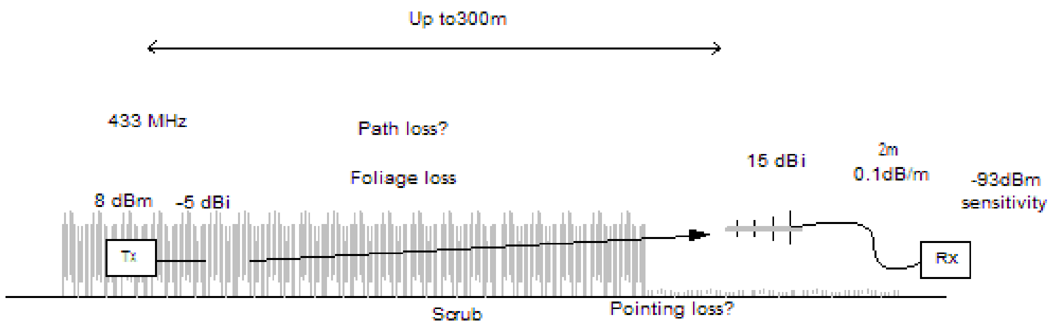
L_F = 0.01 dB. This is not a problem so it can be ignored.

Populating the link budget:

Parameter	**Symbol**	**Value**	**Notes**
Transmit power (dBm)	P_T	+ 8.0	From Tx spec
Transmit cable loss (dB)	L_{CTx}	- 0.0	equation 4
Transmit antenna gain (dBi)	G_{Tx}	- 5.0	
Path Loss(dB)	L_{FS}	- 87.4	equation 3
Other path losses: (dB)		0.0	Rain, atmospheric gases, foliage as required
Receive antenna pointing loss (dB)	L_P	- 0.0	equation 1 then 2
Receive cable loss (dB)	L_{CRx}	- 0.2	2m @ 0.1 dB/m
Signal presented at receiver input (dBm)	P_R	- 84.6	Sum of all the above numbers
Required signal at the receiver (dBm)	P_{Req}	- 93.0	From the receiver spec.
Margin		+ 8.4 dB	the difference between required and received signals.

This is a comfortable margin, so the link should work OK.

A2. With the rocket on the ground, and from the edge of the scrub, there are 2 losses. The first is the path loss, then we must add the loss from the foliage. From the previous calculations we can assume that pointing loss is not a problem.



Frequency is 433 MHz, distance = 0.3 km (300m) from one side to the other. Assuming that the searchers will stand at the front edge and look for a signal, the max path length is 0.3 km. (This could be shortened by walking around the edge)

Path loss = 32.4 + 20 log (433) + 20 log (0.3) = 74.7 dB

From the table above the loss in the scrub at about 500MHz (close enough) will be 0.1 dB/m. The foliage loss is thus 0.1 x 300 = 30 dB.

The total path loss is thus 20 + 71.2 = 91.2 dB

Populating a link budget:

Parameter	**Symbol**	**Value**	**Notes**
Transmit power (dBm)	P_T	+ 8.0	From Tx spec
Transmit cable loss (dB)	L_{CTx}	- 0.0	equation 4
Transmit antenna gain (dBi)	G_{Tx}	- 5.0	
Path Loss(dB)	L_{FS}	- 74.7	equation 3
Other path losses: (dB)		- 30.0	Foliage loss
Receive antenna pointing loss (dB)	L_P	- 0.0	equation 1 then 2
Receive cable loss (dB)	L_{CRx}	- 0.2	2m @ 0.1 dB/m
Signal presented at receiver input (dBm)	P_R	- -101.9	Sum of all the above numbers
Required signal at the receiver (dBm)	P_{Req}	- 93.0	From the receiver spec.
Margin		- 8.9 dB	the difference between required and received signals.

The margin is negative, so the path will not work. The searchers will need to get closer to the rocket to pick up a signal. If they can get within 200m of the rocket they should get a good enough signal.