How to Design a CubeSat Communication System in the Presence of Uncertainty - Using the Example of WUSAT-4

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Abstract

CubeSat missions are very popular as University projects as they give students a hands-on way of learning space-engineering skills, however they are characterised by uncertainty as university teams often lack funds and resources. The communication subsystem is heavily affected by this uncertainty, but without an initial design for this subsystem it is difficult for other subsystems to be developed because of the interrelated nature of the CubeSat's subsystems. This paper presents an approach to handle this uncertainty so that an initial communications subsystem can be designed. The theoretical background of satellite communications is reviewed to outline the key parameters which must be known to design a communications subsystem, then estimates are made for these values based on a review of off-the-shelf-components, previous CubeSat missions and the international telecommunications union's radio regulations. Finally, these estimates are used to create a link budget using the WUSAT-4 (Warwick University Satellite - a satellite designed by students at the University of Warwick) mission as an example - it was found that the WUSAT-4 satellite could use an omnidirectional antenna to achieve a data download rate of 19.6 kbps even at an orbital altitude of 665km.

Keywords: CubeSat; Link Analysis; Modulation, Nanosatellite.

1 Introduction

CubeSat projects are often run by universities because they are a relatively cheap and accessible way for students to get hands-on experience working on satellites.

CubeSats are a type of nanosatellite which follow a specification laid out by two professors from Stanford and California Polytechnic State University [1], such that they can be integrated within an ejection device called a P-POD. The P-POD-CubeSat system makes it easy for launch providers to integrate CubeSats as a secondary payload in their launch vehicle. CubeSat projects have become very popular in recent years – the first launch of a CubeSat was in 2003 [2], the one-hundredth was in 2013 [2] and recent estimates from Kulu suggest that almost 2000 CubeSats had been launched by 2022 [3]. Many of these CubeSats are university projects. However, university CubeSat projects are often faced with the compounding issues of a lack of funds and a lack of resources. Their nature as university projects can thus create a lot of uncertainty when it comes to the design and development of the satellite.

For example, CubeSats require a ground station, or ground station network, to communicate with when they are in space, however not all universities will have this infrastructure – if they don't, then buying such a system or paying to use a ground station service can be expensive. Ground stations in different locations may be exposed to different levels of noise which can severely affect the function of the communication link. Additionally, different ground stations will have different gains, and will be exposed to different amounts of noise, which can affect how strong of a received radiofrequency (RF) signal they need to be able to communicate with the space segment.

Furthermore, in the initial phases of the mission, the launch and launch provider for the CubeSat will not necessarily be known, but the orbital parameters of the satellite, such as orbital altitude and inclination, can drastically change the demand on the communication system. This presents a major difficulty in the design of the entire satellite; a CubeSat is a very interlinked system, and the requirements on other subsystems, such as the electrical power system, can heavily depend on the communication subsystem. So, whilst there is inherent uncertainty in university CubeSat missions, this must be dealt with in order for the mission to progress.

As such, this paper intends to present an approach to dealing with this uncertainty. This will be done by outlining the theoretical background that the satellite link works upon, then constraints such as the International Telecommunications Union's (ITU) Radio Regulations will be outlined, and estimates for some key parameters in the communications system will be made based off the experiences of previous CubeSat missions. Finally, this will be synthesized using the WUSAT-4 (Warwick University Satellite - a CubeSat designed by students at the University of Warwick) communications subsystem as a case study.

2 Literature Review

Most CubeSat missions use RF communications to fulfill the essential functions of telemetry, tracking and command (TT&C) of the satellite. This involves both an uplink, where the ground station sends data to the satellite, and a downlink, where the satellite sends data to the ground station. For most CubeSat missions, the downlink is the more constrained of these, as the data rate must be higher but the power available for the transmitter is lower [4].

2.1 The WUSAT-4 mission

The aim of the WUSAT-4 mission is to carry an automated biological experiment to low earth orbit. The mission will require that command signals be uploaded to the satellite and that experimental data be downloaded. One of the constraints for the mission is that it will not use an attitude control system to reduce complexity, and as such the satellite must use an omnidirectional antenna.

2.2 Theoretical Background

In order to highlight the key mission parameters which affect the design of the CubeSat's communication system, the theoretical background for this must first be reviewed.

2.2.1 Channel Capacity

Much of the design of the communication system of a CubeSat revolves around the signal-to-noise ratio S/N received at the ground station, which is the ratio of the received signal power to the receiver noise power, and is often given as a decibel value in terms of dBW or dBmW. This can also be described in terms of carrier-to-noise density, C/N_0, which is the ratio of carrier power to noise power per unit bandwidth, or even in terms of the energy per bit to noise power spectral density ratio, E_b/N_0. These terms are different, but all describe the strength of a signal compared to noise existent at the point of the receiver in the satellite link, which determines how much data can be transmitted across the communication link.

The theoretical maximum amount of data that can be transmitted through a noisy channel is defined by the Shannon-Hartley theorem:

$$C = B \times log_2(1 + \frac{S}{N}) \tag{1}$$

Where C is the Channel Capacity in bit/s, B is the channel bandwidth in Hz, and S/N is the signal to noise ratio, where S is defined as the received signal power in Watts and N is the noise power at the receiver, also in Watts [5]. This equation describes one of the main trade-offs which is encountered when designing the communications system of a CubeSat, which (for a fixed bandwidth) is between data-rate and power. However, this is not the whole story, as the Shannon-Hartley theorem describes *theoretically* achievable maximum data transmission. The actual data transmission achieved depends on the modulation type and error-correction types employed by the communications system.

Different types of modulation and coding can be used to achieve different levels of resistance to noise in the satellite link. Noisy channels are characterised by the presence of errors, which for the digital communications used by most CubeSats is described in terms of a bit error rate (BER) or a bit error probability (BEP). The specific BEP for a given type of modulation and coding can then be calculated given the E_b/N_0. For example, the BEP for a RF link using direct encoding and quaternary phase shift keying (QPSK) with no channel coding is given by the equation below [6]

$$BEP = \frac{1}{2} erfc(\sqrt{\frac{E_c}{N_0}}) \tag{2}$$

where

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-u^2}\, du \tag{3}$$

One of the roles of the communications engineers would thus be to choose a modulation and coding scheme that minimises this to an acceptable level. The actual spectral efficiency of a chosen modulation and coding scheme, as opposed to the hypothetical capacity given by the Shannon-Hartley theorem, can then be given by:

$$\Gamma = \frac{log_2 M \rho}{(1+\alpha)} \tag{4}$$

Where Γ is the spectral efficiency of the scheme in bits/s/Hz, M is the number of symbols used in the modulation scheme (for example 2 for binary phase shift keying (BPSK) and 4 for QPSK), ρ is the code rate of the scheme, which describes the proportion of redundant bits used for error correction, and α is the roll-off factor of the bandpass filter used [6].

The modulation type and coding for the RF link are chosen to maximise the data rate and minimise the BEP of the communication link. However, the data rate is still heavily dependent on the S/N, and so this one of the main parameters that the CubeSat communication system must be designed for.

2.2.2 Link Equation and Friis Free Path Loss Equation

As the RF signal travels through space from the transmitter to the receiver, it experiences power losses from several different sources, but by far the biggest is the free-space path loss associated with the spreading of the RF waves following the inverse square law. This can be summarised in a variant of the Friis transmission formula [7]:

$$S/N = \frac{P_t G_t G_r}{(\frac{4\pi d}{\lambda})^2 k T_s B} \tag{5}$$

Where P_t is the transmitted RF power, G_t and G_r are the gain of the transmitting and receiving antennas respectively, d is the distance between the transmitter and the receiver, λ is the wavelength of the RF wave, k is Boltzmann's constant, T_s is the system noise temperature of the receiver in K and and B is the noise bandwidth of the system. The free-space path loss itself is given by $(\frac{4\pi d}{\lambda})^2$. It can be seen that, in order to ensure an acceptable BEP for the communication link, all these parameters must be known. It can also be seen in this equation that the S/N ratio is very dependent on the distance between transmitter and receiver, and a small change in this value could make a big change in the requirements for P_t for example. This is part of what makes the uncertainty in the orbital parameters of a CubeSat mission such an issue for designers.

2.2.3 Ground Station Noise

Each element in the chain of communication within a ground station contributes to the noise in the system, which can result in complex calculations if it is necessary to estimate ground station noise. However, the overall noise of a receiver can be summarised by a representative value, called the noise figure (NF) - this value can then be used in a link analysis to calculate the noise power at the receiver.

2.2.4 Slant Range

Of course, since the ground station can start communicating with the satellite as soon as it passes over the horizon, the actual maximum distance (which is needed to quantify the maximum free-space path loss) between the transmitter and receiver can be much greater than the orbital altitude - this is calculated by the slant equation:

$$D = B(\sqrt{\frac{r^2}{B^2} - cos^2(\epsilon)} - sin(\epsilon)) \tag{6}$$

Where D is the slant range (maximum distance between the satellite and ground station when the satellite is above the horizon), r is the distance between the geocenter and the satellite, B is the distance between the geocenter and the ground station and ϵ is the minimum elevation angle above the horizon line which is needed to communicate with the satellite (this is normally around 5).

2.2.5 Other Losses

Whilst the free-space path loss is certainly the biggest power loss in a communications link, there are many other losses which must be considered. There is a large amount of detail which could be analysed when it comes to these losses, however for the purposes of this paper, and as is appropriate at the initial stage of a CubeSat mission design, these shall not be dissected in great detail. These losses can be summarised by

$$[LOSSES] = [FSL] + [RSL] + [AML] + [PL] \tag{7}$$

where FSL is the free-space path loss, given above, RFL is the receiver feeder loss, AML is the antenna misalignment loss, AA is the atmospheric absorption loss and PL is the polarisation mismatch loss [8] - values shown in square brackets are used to indicate logarithmic values. The link budget equation can the be rewritten as

$$[P_R] = [EIRP] + [G_R] - [LOSSES] \tag{8}$$

where EIRP (Effective Isotropic Radiated Power) is a standard way of measuring the power radiated from an antenna. This is the equation that is then used to perform the link analysis for the satellite communication system.

3 Methodology

This paper will show how informed estimates can be made for all of the vast number of unknowns when it comes to designing the communications for a CubeSat mission. This will be done with the assumption that the CubeSat mission will have a low earth orbit (LEO), as many earth-observation CubeSats do. It will also be assumed that the ground station is also unknown or has not been built yet. This paper shall then apply this approach and these estimates to close a link budget for the WUSAT-4 mission. The parameters which need to be estimated or (decided by the design team) to do so are summarised in table 1

Whilst ideally a systematic approach should be taken to make estimates for these values, information about this wide range of parameters must come from a wide range of sources. In addition to this, information is sparse when it comes to some of these variables - for example receiver noise of commercial of-the-shelf (COTS) ground stations.

Table 1: Parameters Required for WUSAT-4 Link Budget

Space Segment	Ground Segment	Orbital Parameters	Loss	Others
Antenna Gain	Antenna Gain	Altitude	Antenna Misalignment Losses	Uplink Frequency
Transmitter EIRP	Transmitter EIRP	Inclination	Atmospheric Absorption Loss	Uplink Bandwidth
Receiver Noise	Receiver Noise	-	Polarization Mismatch Loss	Downlink Frequency
-	-	-	-	Downlink Bandwidth

4 Results & Discussion

4.1 Frequency and Bandwidth

The ITU sets rules for the allocation of frequency and bandwidth for satellite missions, given in the RR - CubeSats are no exception to this rule. The satellite operator must apply for a licence from the national agency in which they are based who the distribute licences based on the ITU's rules. The national agency in charge of this process in the United Kingdom is the Office of Communications (Ofcom). The frequencies allocated to amateur satellite missions by Ofcom are presented in Table 2.

Table 2: Ofcom frequency allocations for amateur satellite missions

VHF	UHF	S-Band
$144 - 146MHz$	$430 - 440MHz$	$2.31 - 2.45GHZ$

This very narrow selection of frequencies for amateur satellite missions narrows down the uncertainty in selecting the frequency considerably - essentially down to 3 options for most CubeSat missions. These can then be chosen based on the required data rate - higher frequencies have the potential to carry higher data rates as they can carry more symbols per second. The frequency chosen then determines the size of the antenna as this corresponds to the wavelength of the RF wave.

4.2 Orbital Parameters

To make estimates for orbital parameters, the most recent CubeSat launches from two organisations providing CubeSat launch brokering services were analysed - one is a commercial organisation, Exolaunch, and the other is a non-commercial organisation, the European Space Agency (ESA) - results are displayed in table 3. For the ESA launches, only CubeSats launched as part of the Fly Your Satellite! scheme, and ESA scheme designed to develop and launch CubeSats from educational institutions, are considered. For the Exolaunch launches, only the last 5 launches were considered and only launches which involved CubeSats were counted.

The apogee is taken for each orbit as this represents the maximum distance that the CubeSat will be from the earth during any orbit - this is the value for distance that must be used for the slant distance and free path loss calculations.

Table 3: Analysis of Launch Data

ESA FYS! [9] [10]				Exolaunch [11]			
Year	No. of Satellites Launched	Apogee (km)	Inclination ($^\circ$)	Year	No. of Satellites Launched	Apogee (km)	Inclination ($^\circ$)
2021	1	550	97.5470	2023	37	545	97.5
2016	3	665	98.2	2022	21	527	97.5
2015	1	422	51.64	2022	12	490	97.4
2012	7	69.47	98.47	2022	29	530	97.4
-	-	-	-	2021	29	527	97.6

In table 3 it can be seen that the majority of recent CubeSat launches have been launched to an inclination of around 97°. The maximum apogee is 665km so this is will be taken as a worst case scenario for which the communications system will be designed. The only outlier in this analysis is the 2015 ESA FYS! launch, as this was deployed from the International Space Station (ISS) rather than being deployed as part of a rideshare mission.

4.3 Ground Station Noise, Gain and Sensitivity

To produce estimates for typical ground station values, data from four OTC ground stations were summarised in table 4.

Table 4: Ground Station Analysis

Ground Station Name	C3S [12]	Alen [13]	Dhruva [14]	ISIS [15]
Gain (dBic)	23.8	10-25	16.3	15.5
Receiver Noise Figure (dB)	1	0.7-1	N/A	2.6
Pointing Accuracy ($^\circ$)	<0.1	0.3	N/A	<0.2
Maximum Transmitted Power (dBmW)	50	N/A	50	50

It is noted from this analysis that the noise figure quoted on some of the datasheets is a bit optimistic, for instance the 0.7-1 dB quoted by Alen Space. The worst value of 2.6dB will be used for the link analysis - again as the communication system needs to work under the worst case scenario.

In addition to this, it can be seen that a gain of around 15dB is typical for a commercial OTC component - this will also be used in the link analysis.

4.4 Losses

4.4.1 Antenna Misalignment Losses^B

The antenna pointing loss can occur both from the ground segment and from the space segment. These losses are normally only a few tenths of a decibel [8]. However, given that the WUSAT-4 satellite will use a omnidirectional antenna, for this mission the losses are likely to be even less. Antenna pointing losses also depend on the strength of the gain of the ground station - for a However, for now a conservative estimate of 0.5dB of pointing losses will be assumed for the link analysis.

4.4.2 Atmospheric and Ionospheric Losses

Atmospheric losses that the RF link will be subject must be accounted for to perform the link budget - however these vary significantly with time and signal frequency as they are composed of several individual effects like rainfall and travelling ionospheric disturbances. As such, for this stage of the satellite mission, it is best to make a worst-case estimate for this, and explore it in more detail further on in the mission development. Based on advice from [8], this shall be assumed to be 1dB.

4.5 WUSAT-4 Link Budget^R

Using the estimates made in the previous sections of the paper, a link budget has been formed for the WUSAT-4 satellite to validate that its use of a low-gain antenna is feasible and to provide a case study for making a link budget in the presence of significant uncertainty.

Some of the values used in the link analysis are parameters which have come from the design of the communication system. For example, WUSAT-4 will use a software defined radio which will use 4-GFSK with forward error correction, which can encode up to 19.6kbps into 10kHz of bandwidth in the UHF range [16]. Given this modulation scheme, a SNR of 10dBmW is desired for a low BER.

It can be seen that for both the uplink and downlink, the link budget can be closed with at least a 3dB design margin.

Table 5: Link Analysis

	Downlink	Uplink
Carrier Parameters		
Bandwidth	10 kHz	10kHz
Frequency	437 MHz	437 MHz
Modulation Type	4GFSK	4GFSK
Baud Rate	19.6 kbps	19.6 kbps
Orbit Parameters		
Apogee	665kM	665kM
Slant Range	2483kM	2483kM
Propagation Losses		
Free Space Loss	153dB	153dB
Pointing Loss	1dB	1dB
Atmospheric Absorption Loss	1dB	1dB
Transmitter		
Transmitted RF Power	33dBmW	50dBmW
Antenna Gain	1.37dB	15dB
Receiver		
Receiver Gain	15dB	1.37dB
Receiver Noise Power	-120dBmW	-120dBmW
Received RF Power	-105.6dBmW	-88.63dBmW
link Margin		
Received SNR	14.4dB	31.37dB
Required SNR	10dBmW	10dBmW
Link Margin	4.4dB	21.37dB

5 Conclusion

The theoretical background behind satellite communications links was reviewed to highlight parameters which are key to the design of a CubeSat's communication system. Then, estimates were taken from a variety of sources for these parameters so that the uncertainty in link calculations could be minimised. Finally, a link analysis was performed for the WUSAT-4 CubeSat mission - this showed that WUSAT-4's omnidirectional antenna concept was feasible, but it also showed how this approach could be use by other university CubeSat groups in the future.

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