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Power Budgets for CubeSat Radios to Support Ground Communications and Inter-Satellite Links

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ABSTRACT CubeSats are a class of pico-satellites that have emerged over the past decade as a cost-effective alternative to the traditional large satellites to provide space experimentation capabilities to universities and other types of small enterprises, which otherwise would be unable to carry them out due to cost constraints. An important consideration when planning CubeSat missions is the power budget required by the radio communication subsystem, which enables a CubeSat to exchange information with ground stations and/or other CubeSats in orbit. The power that a CubeSat can dedicate to the communication subsystem is limited by the hard constraints on the total power available, which are due to its small size and light weight that limit the dimensions of the CubeSat power supply elements (batteries and solar panels). To date, no formal studies of the communications power budget for CubeSats are available in the literature, and this paper presents a detailed power budget analysis that includes communications with ground stations as well as with other CubeSats. For ground station communications, we outline how the orbital parameters of the CubeSat trajectory determine the distance of the ground station link and present power budgets for both uplink and downlink that include achievable data rates and link margins. For inter-satellite communications, we study how the slant range determines power requirements and affects the achievable data rates and link margins.

INDEX TERMS CubeSat, low Earth orbit, ground communications, inter-satellite link, radio link design, power budget, link margin, data rate, SNR.

I. INTRODUCTION

CubeSats are small spacecrafts with a modular structure based on one CubeSat unit (1U), which is a cube with the side equal to 10 cm [1], [2]. This modular structure enables versatile spacecraft designs with regular shapes and various sizes among which the most common are the 1U, the two-unit (2U) with dimensions of 10 cm × 10 cm × 20 cm and mass of 2 kg, the three-unit (3U) with dimensions of 10 cm × 10 cm × 30 cm and mass of 3 kg, or the six-unit (6U) with dimensions of 10 cm × 20 cm × 30 cm and mass of 6 kg. CubeSat spacecrafts are built mostly with commercial off-the-shelf (COTS) components and are launched in orbit as secondary payloads, thus providing a cost effective alternative for space science experimentation. Because of their affordable costs, CubeSats have been included in the NASA Centennial Program and its associated Centennial Challenges, through the Cube Quest Challenge issued in 2014, which seeks to develop and test subsystems necessary to perform deep space exploration using small spacecraft.

Among the various electronic components of a CubeSat, the radio communication system is a critical one, since it enables the CubeSat to exchange information and interact with ground terminals as well as with other CubeSats. The first step in designing the communication system of a CubeSat involves a link budget analysis to determine power requirements, choose appropriate hardware, and establish modulation parameters for signal transmission and reception. However, unlike traditional large satellites for which radio link budgets have been studied extensively and full details on designing the satellite communication system are available in the literature [3], [4], only limited studies of link budgets for CubeSat radios are available in the literature, related to specific CubeSat missions [5], [6]. These, along with the high-level presentation of the communication systems of various CubeSat missions given in the survey papers [7], [8], provide only a narrow perspective on designing communication systems for CubeSats. However, more general studies of link budgets for CubeSats that are decoupled from the specific details of the CubeSat missions are desirable and will be helpful in assessing the software-defined radio (SDR) implementations proposed recently for CubeSat communication systems [9]–[11]. These have emerged in the wider context of software defined electronics [12], which offers flexible implementations for modern telecommunication and measurement systems by using programmable hardware components that can be reconfigured through software. For communication systems, SDRs have been successfully used since the late 1990s and early 2000 years to improve interoperability of the various commercial radio systems and to reduce development and deployment costs [13], [14], and they have the potential to produce a radical change in the way space communication systems are designed and implemented.

Prompted by the limited number of link budget studies for CubeSat radio systems, this paper aims at augmenting existing literature with a study that considers salient parameters influencing the communication system design such as the CubeSat trajectory altitude, inclination, or inter-satellite slant range, along with constraints implied by SDR platforms.

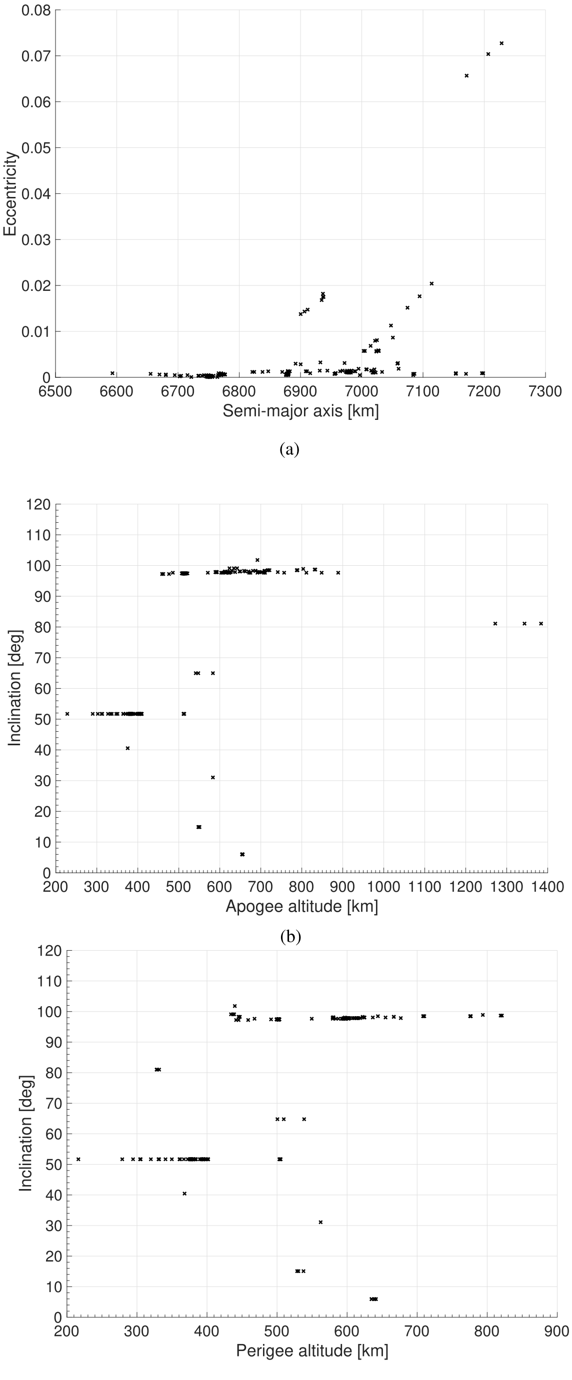
The paper is organized as follows: Section II reviews characteristics of CubeSat missions in low Earth orbit (LEO) followed by an outline of radio link design in Section III. Sections IV and V present the analysis of the CubeSat power budget for the ground station and inter-satellite links, respectively. Final remarks and conclusions are given in Section VI.

II. CUBESAT MISSIONS IN LOW EARTH ORBIT

The CubeSat standard for small satellites was developed in the late 1990s and early 2000 years, being formally introduced in [16] and [17], with over 100 manifested CubeSat missions documented in 2013 [18] and more than 250 CubeSats currently included in the NORAD two-line element (TLE) data sets [15]. Many CubeSat missions consist of a single satellite launched and operated individually to perform specific science experiments, but they can also include multiple CubeSats that are deployed in clusters and establish inter-satellite links to form distributed satellite sensor networks in space [19]–[21].

In our study of radio link power budgets for CubeSat missions we will assume that CubeSats are placed in low Earth orbit at altitudes ranging between 200 km and 800 km, with circular trajectories and inclinations of either 52° or 98°. This assumption is supported by the CubeSat orbital parameters recorded in the TLE data maintained by NORAD and shown in Fig. 1. As can be seen from Fig. 1(a), of the 258 CubeSats whose information is available in [15], the majority have trajectories with eccentricities very close to zero. Furthermore, the apogee and perigee altitudes of most CubeSat missions are very similar, which also indicates almost circular orbits. In addition, from Fig. 1(b)-(c) we note that, with few exceptions, most CubeSat missions launched at altitudes below 500 km have trajectory inclinations of 52°, while those launched above 500 km have trajectory inclinations of 98°.

A CubeSat flying in LEO is equipped with multiple subsystems, which are needed to provide support and power to the science instruments and to transmit the collected data to a ground station for further processing, analysis, and archiving. While physical configuration of CubeSats depends on the actual science experiment to be performed, the main components of a CubeSat are independent of its science mission and are outlined in the block diagram shown in Fig. 2. As seen from Fig. 2, beside the science instruments which are supposed to capture the data related to the observed parameters, a CubeSat spacecraft includes a power subsystem, which is required to power-up all the other subsystems, an onboard computer that performs the data acquisition and processing



(a)

(b)

(c)

FIGURE 1. CubeSat orbital parameters as recorded by NORAD [15].

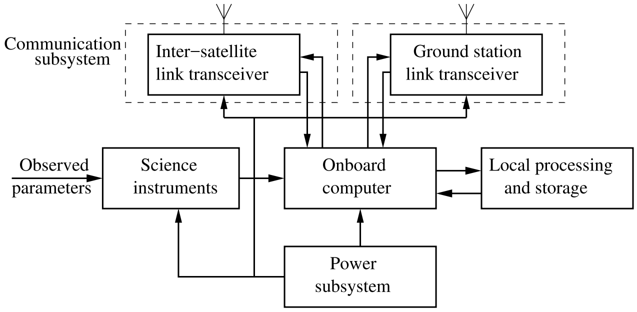


FIGURE 2. Block diagram outlining the main subsystems of a CubeSat.

and controls all of the other CubeSat functions, and the communications subsystem that establishes links with the mission ground station and/or with other CubeSats that may be part of the mission. In missions involving a single CubeSat only the ground station transceiver shown in Fig. 2 is present, while in missions designed for cluster operation of CubeSats the inter-satellite transceiver is also included to establish inter-satellite communication links as required by the mission.

In the case of single satellite missions, the CubeSat collects data related to the science experiment being carried out, performs some local processing of this data, and then transmits the data through a radio link to a ground station where it is further processed, interpreted, and stored. In such missions there is usually no need for an inter-satellite link transceiver, unless the CubeSat needs to establish a link also with other CubeSats or an existing satellite network, such as GlobalStar or Iridium for example, which may be used as alternatives to collect satellite experiment data.

In the case of multiple CubeSats operating in formation, the satellites establish also inter-satellite radio links [6] and set up a space wireless network over which they share observed science data along with ancillary information (position, timing, etc.) that enables them to perform joint/distributed processing of the data. In such a scenario, it is not necessary for all CubeSats to establish radio links to ground stations, as only one (or maybe a few of them) can act as gateways to transmit the science data to a ground station. We note that the CubeSats acting as gateways require to have both radio transceivers present, one to establish the radio link with the ground station, and another one to exchange information with the other CubeSats over the inter-satellite wireless network. The other CubeSats will only need to have the inter-satellite link transceiver to be able to establish the space wireless network.

III. RADIO LINK DESIGN

The goal of radio link design is to ensure that a reliable communication link can be established between a radio transmitter and its associated receiver. In the context of digital communication systems, link reliability is evaluated through the bit error rate (BER) associated with the specific digital modulation scheme that is used to transmit information over the radio link, which depends on the signal-to-noise ratio (SNR) at the radio receiver. Thus, the main objective of radio link design is to establish if sufficient power is available at the radio receiver to close the link, that is to meet a specified SNR value.

For digital modulation schemes, the SNR at the receiver is given by the ratio of the received energy per bit E_b to the noise spectral density N_0. The energy per bit is expressed as

$$E_b = \frac{P_r}{R}, \tag{1}$$

where P_r is the received power in Watts [W] and R is the data rate that is expected to be supported by the radio link in bits per second [bps]. The noise spectral density N_0 is expressed in [W/Hz] and in general is assumed uniform, being expressed in terms of the system noise temperature T_s as

$$N_0 = kT_s \tag{2}$$

where $k = 1.38 \times 10^{-23}$ [J/K] is Boltzmann's constant. We note that the system noise temperature T_s is determined by adding antenna noise temperature T_{ant}, which includes noise sources that are external to the receiver (such as cosmic radiation, solar noise, man-made noise, etc.), and the receiver noise temperature T_r, which incorporates the noise contribution of the various circuit elements that connect the receive antenna to the digital demodulator (feed line, cabling, connectors, front-end band pass filter, low noise amplifier, etc.),

$$T_s = T_{ant} + T_r, \tag{3}$$

with

$$T_r = \frac{T_0}{L_r}(F - L_r), \tag{4}$$

where $T_0 = 290$ K is the reference temperature, L_r denotes the line and connector losses from antenna to receiver amplifier, and F is the noise figure of the amplifier [4, Sec. 13.3].

Combining eqs. (1) and (2) the received SNR is written as

$$\text{SNR} = \frac{E_b}{N_0} = \frac{P_r/R}{kT_s}. \tag{5}$$

Given the available power P_t of the radio transmitter, the power value P_r at the receiver is determined using the free-space propagation model [4, Sec. 13.3]

$$P_r = \frac{P_t G_t G_r}{L_p}, \tag{6}$$

where power values P_t and P_r are expressed in Watts [W], G_t and G_r are the transmit and receive antenna gains, respectively, and L_p is the propagation path loss given by

$$L_p = \left(\frac{4\pi d f}{c}\right)^2, \tag{7}$$

with d being the distance between the radio transmitter and receiver, f the radio signal frequency, and c the speed of light. Combining eqs. (5), (6), and (7), we obtain the link budget equation commonly used to evaluate a digital data radio link:

$$\text{SNR} = \frac{E_b}{N_0} = \frac{P_t G_t G_r}{kT_s R L_p}. \tag{8}$$

Because the link budget equation (8) is essentially a succession of product operations of multiple terms, it can be written also in a more convenient form that involves the decibel (dB) representations of the individual terms that appear in it:

$$\begin{aligned} \mathrm{SNR}_{dB} &= 10\log_{10}\left(\frac{E_b}{N_0}\right) \\ &= 10\log_{10}\left(\frac{P_t G_t G_r}{k T_s R L_p}\right) \\ &= P_{t,dBm} - 30 + G_{t,dBi} + G_{r,dBi} - L_{p,dB} \\ &\quad -10\log_{10} k - 10\log_{10} T_s - 10\log_{10} R. \qquad (9) \end{aligned}$$

Using eq. (8) or (9) one can now evaluate the data rate R that can be supported for reliable communication for a given SNR, or identify the minimum SNR required to ensure reliable communication for a specified data rate R. We note that, to ensure robustness of the designed link, in practice additional terms are included in the link budget equations (8) or (9) to account for other link losses and to include a link margin. These will be discussed in more details in the subsequent link budget analysis sections.

IV. POWER BUDGET FOR THE GROUND STATION LINK

In general, a CubeSat is connected to a ground station through a duplex radio link consisting of uplink, over which the CubeSat transmits data to the ground station, and downlink, over which the ground station transmits commands to the CubeSat. The value of the propagation path loss, which is shown in eq. (7), depends on the link distance d between the CubeSat and the ground station, and on the frequency used for transmission.

A. DETERMINING DISTANCE FOR THE GROUND STATION LINK

The distance d between CubeSat and the ground station is determined by the orbital parameters of the CubeSat trajectory, which are determined for LEO satellites with circular orbits as outlined in [4, Sec. 5.3.1]. The distance value d varies between minimum and maximum values $d_{\min}$ and $d_{\max}$, which correspond to the distances between ground station and CubeSat at its orbit trajectory pole and effective horizon, respectively. Following [4, Sec. 5.3.1] we have:

$$d_{\min} = R_E \frac{\sin(\lambda_{\min})}{\sin(\eta_{\min})}, \qquad (10)$$

where $R_E = 6,378$ km is the Earth radius, $\lambda_{\min}$ is the minimum Earth central angle between the satellite's ground track and the ground station and $\eta_{\min}$ is the minimum nadir angle. Knowing the latitude and longitude coordinates of the ground station and CubeSat orbit pole, $(lat_{gs}, long_{gs})$ and $(lat_{pole}, long_{pole})$, respectively, we have that

$$\begin{aligned} \sin(\lambda_{\min}) &= \sin(lat_{pole})\sin(lat_{gs}) \\ &\quad + \cos(lat_{pole})\cos(lat_{gs})\cos(\Delta long), \qquad (11) \end{aligned}$$

where $\Delta long = long_{gs} - long_{pole}$. The CubeSat orbit pole coordinates are determined by its orbit inclination $incl$ along with the instantaneous ascending node longitude L_{node} as follows

$$\begin{aligned} lat_{pole} &= 90^\circ - incl \\ long_{pole} &= L_{node} - 90^\circ. \qquad (12) \end{aligned}$$

We note that because the CubeSat orbit relative to the Earth changes due to the Earth's rotation, L_{node} is different for distinct passes of the CubeSat over the ground station, and that some of its values will be outside of the ground station horizon, in which case the CubeSat will not be visible to the ground station.

The minimum nadir angle is implied by

$$\tan(\eta_{\min}) = \frac{\sin(\rho)\sin(\lambda_{\min})}{1 + \sin(\rho)\cos(\lambda_{\min})}, \qquad (13)$$

where

$$\sin(\rho) = \frac{R_E}{R_E + H} \qquad (14)$$

is the angular radius of the Earth as seen from the CubeSat, with H being the CubeSat trajectory altitude.

Similarly, for $d_{\max}$ we have that

$$d_{\max} = R_E \frac{\sin(\lambda_{\max})}{\sin(\eta_{\max})}, \qquad (15)$$

where

$$\sin(\eta_{\max}) = \sin(\rho)\cos(\varepsilon_{\min}) \qquad (16)$$

and

$$\lambda_{\max} = 90^\circ - \varepsilon_{\min} - \eta_{\max}, \qquad (17)$$

with $\varepsilon_{\min}$ being the effective horizon elevation of the CubeSat trajectory.[1]

Beside the distance between CubeSat and ground station, the orbital parameters of the CubeSat trajectory determine also the total time T the CubeSat is in view of the ground station. For a given pass that corresponds to a CubeSat orbit that is visible from the ground station the value of T is given by

$$T = \frac{P}{180^\circ} \cdot \arccos\left[\frac{\cos(\lambda_{\max})}{\cos(\lambda_{\min})}\right], \qquad (18)$$

where the arccos(·) function yields values in degrees and

$$P = 1.658669 \cdot 10^{-4} \cdot \sqrt{(R_E + H)^3} \qquad (19)$$

is the orbit period of the CubeSat in minutes. We note that the value of T is very sensitive to the value of the effective horizon elevation of the CubeSat trajectory $\varepsilon_{\min}$, and that the maximum time in view is

$$T_{\max} = P\frac{\lambda_{\max}}{180^\circ}. \qquad (20)$$

$T_{\max}$ corresponds to the case when the CubeSat trajectory passes overhead relative to the ground station and $\lambda_{\min} = 0$,

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[1] The true geometrical horizon corresponds to elevation $\varepsilon = 0^\circ$. However, due to ground features such as buildings or trees, the CubeSat enters effectively in sight of the ground station only when its elevation $\varepsilon \geq \varepsilon_{\min}$.

TABLE 1. **CubeSat orbit inclination 52°, L_{node} = 56.3052°, and ground station in Norfolk, VA.**

H [km]	$d_{\min}$ [km]	$d_{\max}$ [km]	T [min]	$T_{\max}$ [min]
300	1,052	1,500	4.7549	6.4014
400	1,092	1,805	6.4914	7.9086
500	1,139	2,078	7.9749	9.2069

TABLE 2. **CubeSat orbit inclination 98°, L_{node} = 66.3052°, and ground station in Norfolk, VA.**

H [km]	$d_{\min}$ [km]	$d_{\max}$ [km]	T [min]	$T_{\max}$ [min]
500	1,556	2,078	6.3535	9.2069
600	1,601	2,329	7.9245	10.4315
700	1,651	2,563	9.3262	11.6036

TABLE 3. **CubeSat orbit inclination 52°, L_{node} = 78.6208°, and ground station in San Antonio, TX.**

H [km]	$d_{\min}$ [km]	$d_{\max}$ [km]	T [min]	$T_{\max}$ [min]
300	544	1,500	6.1893	6.5014
400	608	1,805	7.6442	7.9086
500	680	2,078	8.9722	9.2069

TABLE 4. **CubeSat orbit inclination 98°, L_{node} = 88.6208°, and ground station in San Antonio, TX.**

H [km]	$d_{\min}$ [km]	$d_{\max}$ [km]	T [min]	$T_{\max}$ [min]
500	1,538	2,078	6.4445	9.2069
600	1,583	2,329	8.0003	10.4315
700	1,633	2,563	9.3929	11.6036

and, as discussed in [4, Sec. 5.3.1], if the CubeSat passes are approximately evenly distributed in off-ground track angle, then the average pass duration is about 80% of $T_{\max}$, with about 86% or more of the passes longer than half $T_{\max}$.

In Tables 1 and 2 we illustrate the distance and view times for CubeSats with different trajectory inclinations and altitudes, and a ground station located in Norfolk, VA,[2] while in Tables 3 and 4 we show the values for a ground station located in San Antonio, TX.[3]

Summarizing the values in Tables 1 – 4 we note that the distance between a CubesSat and a ground station located in the continental United States ranges from 500 km to about 2,600 km, with view times of 5 – 10 minutes during which the CubeSat and the ground station may exchange information.

B. FREQUENCY SELECTION AND LINK CHARACTERISTICS

CubeSats commonly use frequencies in the VHF and UHF bands for establishing communication links with ground stations, with focus on the amateur radio frequencies in the 2 m VHF bands (144 MHz to 148 MHz) and 70 cm UHF bands (420 MHz to 450 MHz) [7]. To minimize the value of the propagation path loss and to reduce the power requirements for the CubeSat transmitter, the 2 m bands are used for the uplink (CubeSat-to-ground station), while the 70 cm bands are used for the downlink (ground station-to-CubeSat). Assuming a maximum distance of 2,600 km between the CubeSat and the ground station, the uplink path loss value at 146 MHz is 144 dB, while the down link path loss value at 437 MHz is 153.56 dB, corresponding to a 9.56 dB lower loss in the uplink compared to the downlink.

In terms of antennas, CubeSats rely mostly on omnidirectional dipole antennas for transmission in VHF bands with no directional gains (0 dBi), while ground stations usually have directional antennas with satellite tracking abilities and antenna gains between 10 and 15 dBi. Such gain values are usual for Yagi antennas in the VHF and UHF radio bands, and our link budget analysis assumes that the ground station transmit and receive antenna gains are 12.34 dBi and 15.5 dBi, respectively.[4]

For the CubeSat transceiver minimal losses of approximately -0.2 dB will be included in the link budget calculations. This corresponds to an absolute loss term of $L_c \simeq 0.955$ for the CubeSat and is justified by the fact that the radio hardware along with the antenna and related connections are very close to each other due to the physical dimensions of the CubeSat. Assuming a noise figure $F_c = 7$ dB (5 in absolute value) for the CubeSat receiver, corresponding to the USRP B-200 SDR, we obtain from eq. (4) a receiver noise temperature of $1,228$ K for the CubeSat receiver.

For the ground station losses of about -3 dB will be considered in the link budget, corresponding to an absolute loss term $L_{gs} \simeq 0.5$. This loss is due in part to the cable connecting the ground station antennas and radio hardware, which for a two story building can be of the order of 150 feet from the rooftop to the radio room. Assuming 1.5 dB/100 feet of cable this implies 2.25 dB loss to which an additional loss of 0.75 dB for the various connectors is added. A lower noise figure $F_{gs} = 3$ dB (or 2 in absolute value) is assumed for the ground station receiver, for which eq. (4) resulting in a receiver noise temperature of 870 K for the ground station.

For the ground station uplink the antenna noise temperature is taken to be equal to the reference temperature $T_0 = 290$ K, while a lower antenna noise temperature of 150 K is assumed for the downlink.

C. LINK BUDGET ANALYSIS

For the power budget analysis we assume that the CubeSat transmitter operates at low power levels, which may be achieved by using a software defined radio (SDR) transmitter with no additional amplifiers. This assumption is motivated by the fact that CubeSats rely exclusively on their onboard power system, which has limited capabilities to support batteries and solar panels due to the small physical volume of the CubeSat spacecraft. Specifically, our link budget analysis assumes a transmit power level of 15 dBm (about 31.62 mW) for the CubeSat, corresponding to a Universal Software Radio Platform (USRP) B-200 with no additional amplifiers [22].

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[2] Coordinates for Norfolk, VA, are 36.8865° N, 76.3052° W.

[3] Coordinates for San Antonio, TX are 29.5831° N, 98.6208° W.

[4] These gain values correspond to the 2MCP14 and 436CP30 amateur radio antennas, respectively, from M2 Antenna Systems, Inc., and are currently used in the Old Dominion University ground station.

TABLE 5. Example of power budget for the ground station link.

	Uplink	Downlink
Frequency	146 MHz	437 MHz
Transmit power P_t	15 dBm	50 dBm
Transmitter loss	0.2 dB	3 dB
Transmit antenna gain G_t	0 dBi	15.5 dBi
Propagation path loss L_p	144 dB	153.76 dB
Other propagation losses	4 dB	4 dB
Receive antenna gain G_r	12.34 dBi	0 dBi
Receiver noise temperature T_r	870 K	1,228 K
Antenna noise temperature T_{ant}	290 K	150 K
System noise temperature T_s	1,160 K	1,378 K
$10\log_{10} T_s$	30.64 dBK	31.39 dBK
Boltzmann constant		
$10\log_{10} k + 30$	−198 dBm/K/Hz	−198 dBm/K/Hz
Data rate R	2,400 bps	1 Mbps
$10\log_{10} R$	33.80 dBHz	60 dBHz
Received SNR	12.70 dB	11.35 dB
SNR required for 10^{-5} BER (BPSK, QPSK, 8-FSK with FEC)	> 9.5 dB	> 9.5 dB
Link margin	≤ 3.2 dB	≤ 1.85 dB

We note that similar power levels have been reported in the literature for CubeSat transmitters [23], and this value is conservative, as transmit powers as high as 30 dBm (1 W) have also been mentioned for CubeSat missions [24].

For the ground station transmitter higher transmit power levels may be assumed. This is motivated by the fact that for the ground station transmitter the only restriction on transmit power is implied by its operating license, and in our link budget analysis we assume a transmit power level of 50 dBm (100 W), which can be achieved by using amateur radio equipment. However, this assumption does not restrict the implementation of the ground station transmitter to amateur radio equipment, and if it is desired to implement the ground station transmitter using a SDR such as the USRP, a two-stage amplifier with 10 dB in the fist stage and 25 dB in the second stage may be used to increase the output power of the USRP transmitter to reach the desired level of 50 dBm.

With these power levels for the CubeSat and ground station transmitters, we note from the power budget summarized in Table 5 that, with digital modulation schemes commonly used in satellite communication systems that include forward error correction (FEC) coding [4, Sec. 13.3.3], low data rates of the order of 2.4 kbps can be achieved in the uplink, while data rates as high as 1 Mbps are available in the downlink, with link margins of 3.2 dB and 1.85 dB, respectively.

We conclude the ground station link analysis by noting that, the low data rate achievable over the CubeSat uplink in conjunction with the limited time the CubeSat is visible from the ground station, imposes strict limits on the amount of information that may be transferred from the CubeSat to the ground station during one pass over the ground station. For example, at the rate of 2,400 bps considered in the power budget example in Table 5, a short pass of 4.75 min would allow the transfer of about 684 kbits of data, while for a longer pass of about 9.4 min about 1.3 Mbits of data would be transferred. To put these numbers in perspective, we note that a VGA image with a size of 640 × 480 pixels encoded at $1.5 - 2$ bits/pixel in JPEG format with typical settings [25] would require about 614 kbits to be transmitted. To overcome the limitations associated with the low uplink data rates and CubeSat visibility times at the ground station, novel approaches have been proposed recently, which consider a network of ground stations rather than a single one to acquire large amounts of information from CubeSats [26].

TABLE 6. Inter-satellite path loss values for L-band and S-band frequencies and different slant range values.

Slant range d [km]	10	25	100	1,000
L-band path loss [dB] for 1.265 GHz	114.48	122.44	134.48	154.48
S-band path loss [dB] for 2.450 GHz	120.23	128.18	140.23	160.23

V. POWER BUDGET FOR INTER-SATELLITE LINKS

Unlike the ground station link case, where one has to consider a duplex radio link with distinct parameters in the uplink and downlink, in the case of inter-satellite links one can focus on a simplex radio link where one CubeSat is the transmitter and another CubeSat is the receiver. In this case, the link distance d is determined by the slant range of the two CubeSats, which represents the line-of-sight distance between them. We note that, when CubeSats are flying in a cluster formation, their position is controlled to ensure that the relative distance between any two CubeSats in the cluster stays within a maximum range, which depends on the mission specifications. The values of the inter-satellite range distance assumed in the literature vary from as low as $10 - 25$ km [8], to 90 km [6], and as high as 1,000 km [27].

A. FREQUENCY SELECTION AND LINK CHARACTERISTICS

Because of the strict constraints imposed by the CubeSat design specifications [2] the antennas used for the inter-satellite radio link are expected to have small size and weight, while also providing link gains with low power consumption. Recently, various types of planar antennas have emerged as meaningful alternatives in this direction [28]. As reported in [28], microstrip patch and slot antennas operating in the L and S satellite frequency bands have sizes compatible with the CubeSat dimensions, and gains ranging from 2.3 dBi to 6.9 dBi depending on their shape and other characteristics.

In the current study of inter-satellite link budgets we assume that the CubeSat antenna gains are 5 dBi for both the transmitter and the receiver, and we consider link frequencies both in the L band (1 – 2 GHz) and in the S band (2 – 4 GHz). The path loss values associated with free-space propagation at specific frequencies in these bands and different CubeSat slant ranges are summarized in Table 6.

Furthermore, transceiver losses similar to those corresponding to the CubeSat transceiver in the ground station link are assumed: hardware/connector loss of about 0.2 dB ($L_c \simeq 0.955$ absolute loss), receiver noise figure $F_c = 7$ dB (5 in absolute value), and receiver noise temperature of 1,228 K. A lower antenna noise temperature of only 22 K is assumed for the inter-satellite link budget.

TABLE 7. Example of power budget for CubeSat-to-CubeSat radio link.

	L-band	S-band
Frequency	1.265 GHz	2.450 GHz
Transmit power P_t	15 dBm	15 dBm
Transmitter loss	0.2 dB	0.2 dB
Transmit antenna gain G_t	5 dBi	5 dBi
Propagation path loss L_p	114.48 dB	120.23 dB
Other propagation losses	2 dB	2 dB
Receive antenna gain G_r	5 dBi	5 dBi
Receiver noise temperature T_r	$1,228$ K	$1,228$ K
Antenna noise temperature T_{ant}	22 K	22 K
System noise temperature T_s	$1,250$ K	$1,250$ K
$10\log_{10} T_s$	30.97 dBK	30.97 dBK
Boltzmann constant $10\log_{10} k + 30$	-198 dBm/K/Hz	-198 dBm/K/Hz
Data rate R	3 Mbps	1 Mbps
$10\log_{10} R$	64.77 dBHz	60 dBHz
Received SNR	10.58 dB	9.6 dB
SNR required for 10^{-5} BER (BPSK, QPSK, 8-FSK with FEC)	> 9.5 dB	> 9.5 dB
Link margin	≤ 1.08 dB	≤ 0.1 dB

B. LINK BUDGET ANALYSIS

For the analysis of the inter-satellite link power budget we start by considering again that the CubeSat transmitter operates at low power levels that correspond to the use of SDR transmitters with no additional amplifiers, and we assume the same transmit power level of 15 dBm (or 31.62 mW) for the CubeSat transmitter along with the use of similar digital modulation schemes with FEC. Under these assumptions, we note from the power budget summarized in Table 7 that, for the lowest inter-satellite link distance of 10 km data rates of the order of 3 Mbps can be achieved in the L band, while data rates of only 1 Mbps are available in the S band, with link margins of 1.08 dB and 0.1 dB respectively.

Because in practice link margins around 2 dB are desirable to ensure that the inter-satellite link is operational even with unforeseen variations of its parameters, establishing reliable high data rate inter-satellite links with 15 dBm transmit power is challenging, even over short distances. While for the 10 km link distance minor power increases of $1 \div 2$ dBm will put the link margin above 2 dB, significantly higher transmit power levels should be used if it is desired to establish a reliable high speed inter-satellite link over distances of 100 km or more. As a compromise, one could lower the data rate on the inter-satellite link by two orders of magnitude to 30 kbps and 10 kbps in the L and S bands, respectively, and take advantage of the implied link gain of 20 dB to extend the range of the link by one order of magnitude, from 10 km to 100 km. Alternatively, the range of the inter-satellite link could be extended to 100 km with no penalty on the link rate if a power amplifier with a 20 dB gain is used in the transmitter. Finally, the range of the link could be extended to $1,000$ km by reducing the data rate along with increasing the transmit power levels.

VI. CONCLUSIONS

In this paper, we studied radio link budgets to support communications between CubeSats and ground stations as well as inter-satellite communications. We outlined how the orbital parameters of the CubeSat trajectory determine the length of the ground station link and studied how the CubeSat slant range affects the path loss for the inter-satellite link. Formal power budgets that include achievable data rates and link margins have also been presented for the ground station and inter-satellite links.

The power budgets for both the ground station link and the inter-satellite link assumed that the CubeSat transmits at low power levels of 15 dBm, which correspond to the use of a SDR platform such as the USRP B-200 with no additional amplifiers. This constraint on transmit power limits the achievable data rates for the ground station uplink and for the inter-satellite link. An additional limitation for the CubeSat uplink to the ground station is implied by the limited time the CubeSat trajectory is visible at the ground station geographic location, which affects the amount of information that can be uploaded by the CubeSat to the ground station during one trajectory pass.

In future work we plan to study methods to overcome the aforementioned limitations on CubeSate data rates and amount of information that can be uploaded to the ground station. Advances in these directions are needed in order to bring CubeSats to the forefront of space exploration. CubeSat data rates may be increased by transmitting at higher power levels that exceed the usual 15 dBm power limit afforded by SDR platforms. This can be accomplished by using larger solar panels and batteries in conjunction with power amplifiers, and may require larger satellite volumes such as 3U or 6U CubeSats to accommodate them. Uploading large amounts of data from CubeSats may be accomplished through a network of ground stations at which the CubeSat is visible at different points in its trajectory and require precise coordination among ground station receivers along with the use of "pause & resume" protocols for information transfer.

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