Designing the Communication Sub-System for Nanosatellite CubeSat Missions: Operational and Implementation Perspectives

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***Abstract*—Over the past decade nanosatellites have emerged as a cost-effective alternative to the traditional large satellite missions, enabling access to space experimentation for universities and other types of small enterprises, which otherwise would be unable to carry them out due to cost constraints. A major challenge when designing nanosatellite systems such as a CubeSats, is implementing the communication sub-system, which is a critical component that determines the specific tasks the satellite is capable of accomplishing. This paper examines operational constraints for CubeSats placed in low Earth orbits and how they impact the design of their communications sub-system.**

***Index Terms*—Nanosatellites, low Earth orbits, CubeSats, path loss, Doppler shift, link budget.**

I. Introduction

Cube satellites or CubeSats are a subset of nanosatellites that have a modular structure with one CubeSat unit (1U) implied by a cube with dimensions of 10 cm $\times$ 10 cm $\times$ 10 cm and mass of up to 1 kg [1], [2]. CubeSats can be built in various sizes such as 1U, 2U, 3U, and 6U, and they can be launched in orbit as secondary payloads at a fraction of the cost of a traditional satellite system, thus bringing space science experimentation within reach for universities. CubeSats are also part of the NASA Centennial Program and its associated Centennial Challenges, through the Cube Quest Challenge that was issued in 2014 and seeks to develop and test subsystems necessary to perform deep space exploration using small spacecraft. As part of Cube Quest, demonstration of deep-space communication capabilities of CubeSats is expected. We note that, implementation of the communication sub-system for a CubeSat mission is a significant endeavor, since this is a critical component that lays the foundation for what types of experiments the mission can pursue and determines the amount of information that can be transmitted back to Earth for analysis and further processing.

CubeSat missions may consist of a single satellite launched and operated individually for basic science experiments, or they can include multiple CubeSats that are deployed in clusters to operate in swarm-like formations as is the case with the QB50 mission [3], whose launching is planned for late 2015 or early 2016 [4]. In the former case, the satellite collects data related to the studied science experiment, performs some basic processing on this data, and then transmits the data using a radio transceiver to a ground station where it is further processed and interpreted. In the latter case, the satellites establish also inter-satellite links [5] and set up a wireless network over which they share observed science data along with ancillary information (position, timing, etc.) which enables them to perform joint/distributed processing of the data. Thus, in this case CubeSats may require two radio transceivers, one for the ground station link and another one for the inter-satellite connections.

Recently, the use of software-defined radios (SDRs) has been proposed to implement the communications sub-system for CubeSats [6], [7], [8]. This approach has been prompted by the emergence of software defined electronics [9], which offers flexible implementations for modern telecommunication and measurement systems and enables reconfigurability of a given electronic system through software and programming. SDRs have been successfully used since the late 1990s and early 200 years to improve interoperability of the various commercial radio systems, and to reduce development and deployment costs [10], [11].

In this paper we present an operational and implementation perspective on the communication sub-system of a CubeSat mission. Specifically, we study requirements associated with the ground station that monitors the CubeSat mission and present a framework which can be used to determine the time interval that a CubeSat will be within line of sight of the ground station. We also present a link budget analysis and outline implementation aspects for CubeSat missions.

The paper is organized as follows: in Section II we outline the main components of a CubeSat placed in low Earth orbit for science experimentation and discuss operational constraints implied by the satellite trajectory. In Section III we study the radio link between CubeSats in orbit and a ground station, followed by presentation of a link budget analysis for the CubeSat-to-ground station radio link in Section IV, which includes link budgets for 1U, 3U, and 6U CubeSats. In Section IV we discuss suitable digital modulation and implementations aspects, and we conclude the paper with final remarks in Section V.

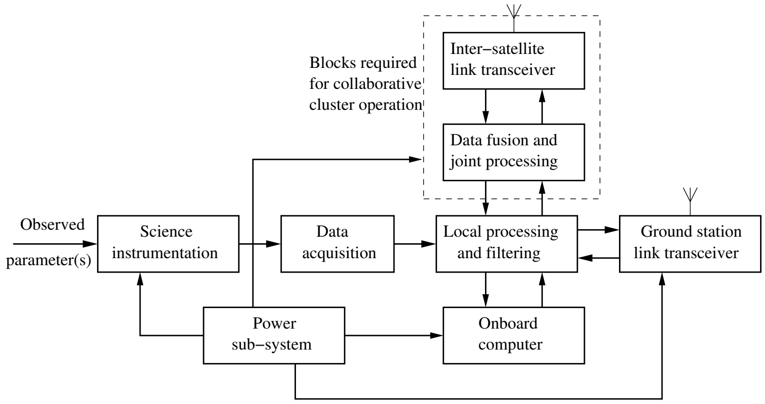

Fig. 1. Block diagram outlining the main components of a CubeSat system

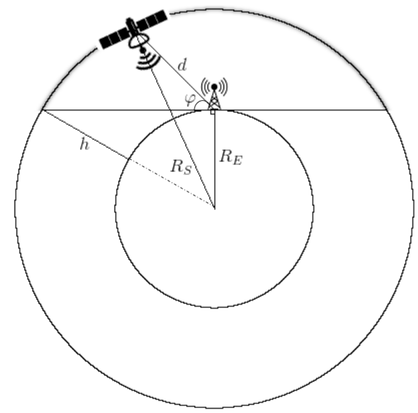

Fig. 2. Schematic description of a CubeSat trajectory in low Earth orbit.

II. Low Earth Orbit Science Experimentation using CubeSat Systems

A CubeSat platform capable of satisfying requirements for science experiments in low Earth orbit (LEO) should include all subsystems needed to support and power the science instruments as well as to transmit the collected experiment data to a ground station for further processing, analysis, and archiving. We note that, while physical configuration of CubeSats depends on the actual science experiment to be performed, the main components of a CubeSat system are independent of the CubeSat science missions and are outlined in the block diagram shown in Fig. 1. Beside the science instruments which are supposed to provide the data related to the observed parameters, a CubeSat system includes a power sub-system with solar panels and batteries to power-up the CubeSat, the onboard computer performing data acquisition and processing, and the communications sub-system for providing the link with the mission ground station as well as links with other CubeSats that may be part of the mission.

When focusing on the design of the communication subsystem of a CubeSat, one should note first that, because they are placed in low Earth orbit, CubeSats are within range of the mission ground station only for a limited time duration, which is usually of the order of a few minutes. For a successful CubeSat mission this duration must enable the information exchange between the CubeSat and the ground station, and determines the amount of information to be exchanged as well as the data rate and the parameters of the digital modulation scheme used for the satellite-to-ground communication link.

Assuming that the satellite flies in an overhead trajectory as illustrated schematically in Fig. 2, the duration T of a CubeSat pass over the ground station is obtained by dividing the arc length corresponding to its trajectory to the tangential speed of the satellite, and is given by

$$T = \frac{\left[2 \arccos\left(\frac{R_E}{R_E+h}\right)\right](R_E+h)}{v}, \tag{1}$$

where $R_E = 6,371$ km is the radius of the Earth, h is the altitude of the CubeSat trajectory, and v is the circular velocity of the satellite. The values of T for flying altitudes typical for CubeSat missions are given in Table I.

TABLE I
CubeSat visibility times at different altitudes for overhead trajectory [12].

Flying altitude h	Tangential speed v	Visibility time T
200 km	7.784 km/s	6.9 min
300 km	7.726 km/s	8.6 min
350 km	7.697 km/s	9.4 min

From Fig. 2 one can also notice that the distance d between the CubeSat and the ground station varies as a function of the elevation angle φ of the satellite above the horizon, and using the geometry of the trajectory in Fig. 2 d is given by

$$d = \sqrt{(R_E+h)^2 - R_E^2 \cos^2\varphi} - R_E \sin\varphi. \tag{2}$$

For illustration, Fig. 3 shows the variation of the distance d between the CubeSat placed in low Earth orbit and the ground station as a function of the elevation angle φ. We note that while Fig. 3 shows the elevation angle ranging from 0° to 180°, in practical scenarios the range of the elevation angle for a LEO satellite is about 160°, starting from at least 10° to no more than 170°, since for elevations outside this practical range the probability of having line of sight visibility tends to zero due to obstructions. Thus, for elevations in the practical range, the maximum distance between the LEO satellite and the ground station is summarized in Table II.

TABLE II
Maximum distance between CubeSats and ground station at different altitudes for overhead trajectory.

Flying altitude h	Maximum distance from ground station
200 km	800 km
300 km	$1,200$ km
350 km	$1,400$ km

III. CubeSat-to-Ground Station Radio Link

The orbital parameters of the CubeSat trajectory influence the characteristics of the radio link connecting the CubeSat system to the ground station and determine its parameters. Specifically, path loss affects the power of the transmitted

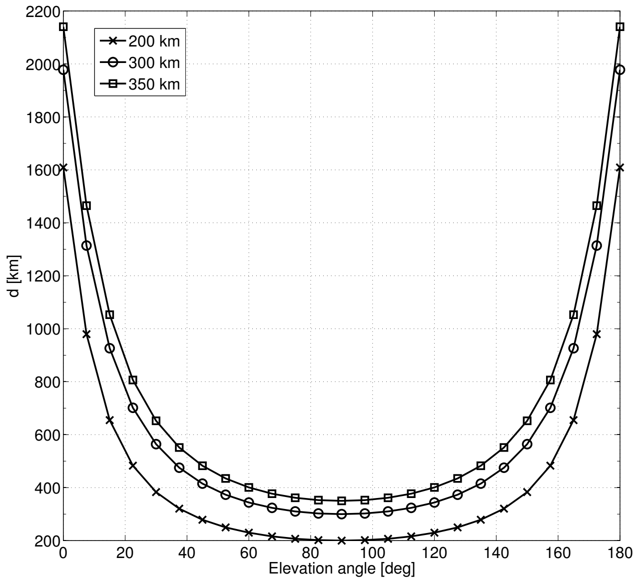

Fig. 3. Variation of distance d from ground station versus elevation above the horizon.

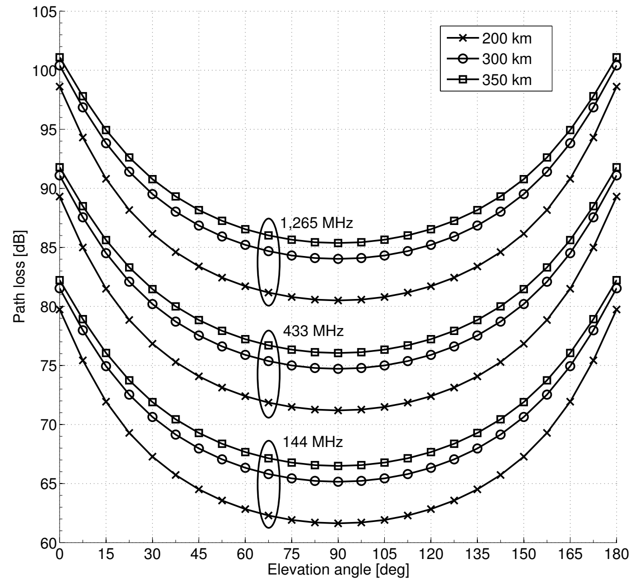

Fig. 4. CubeSat-to-ground station path loss variation as a function of its elevation angle above the horizon for different frequencies and altitude values.

signal and is characterized by free-space propagation path loss model [13]

$$L_p = 20 \log_{10} \left(\frac{4\pi d f}{c} \right), \tag{3}$$

where d is the distance between CubeSat and the ground station given by eq. (2) and shown in Fig. 3, f is the frequency, and $c = 300,000$ km/s is the speed of light. The path loss depends on the frequency used by the CubeSat communication system as well as on the distance between the CubeSat and the ground station, and is illustrated for different frequencies in Fig. 4. We note that there is significant variation of the path loss affecting the CubeSat-to-ground station radio link while the CubeSat is visible from the ground station. As can be observed from Fig. 4, the pathloss is minimum when the CubeSat is at zenith in its trajectory (90° elevation angle), and is maximum when the CubeSat rises/sets over the horizon ($0^\circ/180^\circ$ elevation angles).

From Fig. 4 we note that, as was expected, the lowest path loss values correspond to the VHF band (144 MHz) while the highest path loss corresponds to the L-band ($1,265$ MHz). We also note that, for a given frequency band, the path loss value depends also on the CubeSat trajectory altitude.

Another aspect that must be considered in the study of the CubeSat-to-ground radio link is the shift in signal frequency implied by the Doppler effect, also referred to as the Doppler shift [13], which is given by

$$f_D = f \frac{v}{c} \cos \varphi. \tag{4}$$

The variation of the Doppler shift as a function of angle φ denoting the satellite elevation above the horizon is shown in Fig. 5. As can be observed from Fig. 5, the Doppler shift is

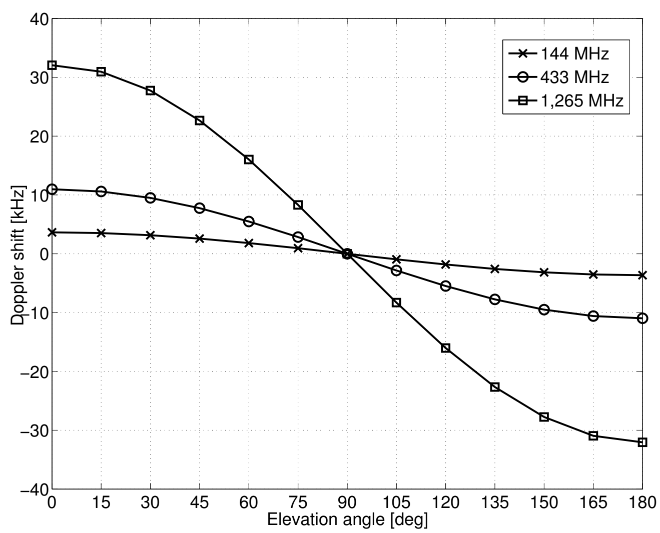

Fig. 5. Doppler shift corresponding to the CubeSat signal at the ground station. The tangential speed of the CubeSat is taken to be $S = 7.7$ km/s.

minimal for the VHF band (around 3.7 kHz for 144 MHz), increases for the UHF band (11.1 kHz for 433 MHz) and becomes significant for the L-band (32.5 kHz for $1,265$ MHz). Depending on the bandwidth allocated to the CubeSat-to-ground station link, correcting the Doppler shift may be necessary to avoid interference to adjacent bands, and will affect the complexity of the communications sub-system of the CubeSat mission [14].

IV. Link Budget Analysis

To develop the link budget for nanosatellite CubeSat missions we use the power budget analysis in [15], which is based on the case study of a meteorology science mission.

According to [15], for a highly adaptive picosatellite with a calculated in-orbit core bus power of 0.864 W a fraction of 5% is allocated to the communications sub-system, that is 0.043 W or 16.33 dBm. The core bus power value scales up by a factor of 10 for a highly adaptive nanosatellite with mass of 10 kg to 8.64 W, of which the same fraction of 5% is allocated to the communications sub-system, that is 0.43 W or 26.33 dBm.

By extrapolating based on these values, one can assume that, depending on the size of the CubeSats used, the power allocated to the communications sub-system of a CubeSat mission is:

- $P_t = 1 \times 0.043 = 0.043$ W$= 16.3$ dBm for a 1U CubeSat,
- $P_t = 3 \times 0.043 = 0.129$ W$= 21.1$ dBm for a 3U CubeSat,
- $P_t = 6 \times 0.043 = 0.258$ W$= 24.1$ dBm for a 6U CubeSat.

We note that these transmit power values are conservative, and higher transmit powers for CubeSat missions have been reported in the literature. For example, in the case of the Istanbul Technical University PicoSatellite-1 mission, the available transmit power for a 1U CubeSat was up to 1 W (or 30 dBm) [16].

To determine the value of the received power P_r at the ground station receiver, we use the free-space propagation model [13]

$$P_r = P_t + G_t + G_r - L_p, \tag{5}$$

where power values, antenna gains, and path losses are expressed in dBm, dBi, and dB units, respectively. For a conservative link budget analysis we assume that omnidirectional antennas are used in the CubeSat and the ground station, having gains equal to 0 dBi, along with a noise floor of 90 dBm. Using eq. (5) along with the path loss values shown in Fig. 4, we obtain the following results:

- In the case of a small mission using a 1U CubeSat, with a transmit power budget $P_t = 16.3$ dBm, the maximum path loss at the highest altitude of 350 km is $L_p = 102$ dB, 92 dB, and 82 dB for L-band, UHF, and VHF respectively, and implies corresponding received power values at the ground station $P_r = -85.7$ dBm, 75.7 dBm, and -65.7 dBm, for L-band, UHF, and VHF respectively. With noise floor at 90 dBm at the ground station receiver we obtain SNR values of 4.3 dB, 14.3 dB, and 24.3 dB for L-band, UHF and VHF, respectively.
- For a mission using a 3U CubeSat with a transmit power budget $P_t = 21.1$ dBm the received power at the ground station is $P_r = -80.9$ dBm, -70.9 dBm, and -60.9 dBm, for L-band, UHF, and VHF respectively, with corresponding SNR values for 90 dBm noise floor at the ground station receiver of 9.1 dB and 19.1 dB, and 29.1 dB for L-band, UHF, and VHF, respectively.
- For a 6U CubeSat mission for which P_t is 3 dBm above that of a 3U CubeSat, the P_r and SNR figures will be 3 dBm above the corresponding values for the 3U CubeSat.

We note that, with a variable path loss implied by the changing distance between the CubeSat transmitter and the ground station receiver, the SNR will vary during the transmission. To maintain a constant SNR at the ground station receiver the CubeSat transmitter may dynamically adjust its transmit power while it is within the radio range of the ground station. Transmitting at constant SNR that matches the required SNR value will also ensure that the CubeSat radio transmits with minimum power and will also contribute to increasing the lifetime of the mission by conserving battery. Power adaptation can be accomplished by using trajectory data to adjust the transmit power P_t of the CubeSat radio once the CubeSat becomes visible to the ground station and establishes a radio link with it.

To conclude this section we mention that, while it is not feasible to use directional antennas in the CubeSat transceiver, they should be considered for use in the ground station, as their use is beneficial to the CubeSat-to-ground station radio link. In addition, the use of pre-amplifiers along with more sensitive receiver front-end boards that can distinguish signals at noise floors of -100 dBm or lower, can further enhance the performance of the radio link.

V. Implementation Aspects

In order to enable cost-effective implementations and provide access to space communication capabilities for university teams launching CubeSat missions, the use of commercial off-the-shelf (COTS) radios is preferred, which are modified for use in space. An important consideration in deciding the implementation of the transceiver that goes on the CubeSat is implied by the parameters of the digital modulation scheme to be used by the communications sub-system of the CubeSat mission, which are determined by the specific requirements of the science experiment performed by the mission. Specifically, knowing the amount of information I to be transmitted to the ground station during one trajectory pass along with the time T the CubeSat is visible from the ground station, one can determine the required data rate R on the CubeSat-to-ground station radio link as $R = I/T$ bits/s.

A digital modulation method suitable for CubeSat missions is frequency shift keying (FSK), which is a power efficient scheme that has been used with other low power low data rate satellite applications (such as global paging via satellite [17]). We note that the uncoded bit error probability for binary FSK modulation over land mobile satellite channels is of the order of 10^{-2} at 15 dB SNR, which can be further improved by the use of appropriate coding techniques [17]. In addition, binary FSK has the advantage of very simple implementation using a basic micro-controller as modulator and demodulator [18]. This makes it ideal for use in the satellite side of the communication sub-system of a CubeSat mission, for transmitting information to the ground station, since in this case simple hardware with low power requirements are usually preferred. However, the supported rate is low, which makes the use of binary FSK less practical for transferring large amounts of data such as images or video, in the short times a CubeSat is visible from the ground station.

To implement more versatile transceivers that support additional modulation schemes and can be incorporated onboard the CubeSats, the use of SDRs has emerged as a meaningful alternative in recent years [7]. SDRs are new types of radios which perform most of the processing in software as opposed to dedicated hardware, and are based on the use of field programmable gate array (FPGA) technology. FPGAs can be easily reprogrammed to suit diverse needs and to enable versatile transmitters and receivers for CubeSat missions, and have the potential to reduce cost and development time while providing significant flexibility in terms of the modulation and demodulation schemes that are available for use. Multiple choices to implement transceivers for both the CubeSat and the ground station are available in this direction. These include flexible boards with transmit-receive capabilities such as the BladeRF [19], which is moderately priced, the Universal Software Radio Peripheral (USRP) [20], which is more expensive but emerged as the leading choice for SDR educational activities [21], or the costly and powerful Wireless Open-Access Research Platform (WARP) [22], [23]. For example, the USRP B200, which is manufactured by Ettus Research (a National Instruments company), provides a fully integrated, single board radio platform with continuous frequency coverage from 70 MHz to 6 GHz and up to 56 MHz of real-time bandwidth, and is a cost effective alternative to the more expensive amateur radio equipment (such as ICOM 910-H radios) to implement the ground station end of the communication sub-system of the CubeSat mission.

Programming and configuration of the SDRs may be accomplished using open-source software development toolkits such as GNU radio [24], [25], as well as software packages for system design, algorithm development, simulation and data visualization such as Matlab and LabVIEW [21]. Currently, Matlab and LabVIEW can be used only in conjunction with USRP SDRs, while GNU radio can be used both as a simulation tool, without any hardware, and as a programming tool for multiple SDRs boards including USRP, BladeRF, and others.

VI. Conclusion

In this paper, we studied the design of the communication sub-system for CubeSat systems by focusing on the operational constraints of the mission when the satellites are placed in low Earth orbit. We derived the expression of the duration of a CubeSat pass over a ground station, as well as the distance between the CubeSat and the ground station, and used these expressions to study the corresponding path loss and Doppler shift for the CubeSat-to-ground station radio link. Using data available in the literature, a conservative link budget analysis was performed, and it was shown that SNRs of the order of $10-20$ dB can be achieved, which, when used in conjunction with digital modulation schemes and error correction codes, imply acceptable bit error rate levels.

In terms of implementations, SDRs have emerged as suitable candidates for implementing versatile transceivers that can be used in CubeSat missions.

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