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Antonio C. R. do Nascimento Jr.[a], Gabriel Teodoro[a], Jefferson Mika[a], Mateus M. B. Costa[a], and Gary B. Hughes[b]

j.nascimento@grad.ufsc.br
gabriel.teodoro@grad.ufsc.br
jefferson.mika@grad.ufsc.br
mateus.magalhaes@grad.ufsc.br
gbhughes@calpoly.edu

[a]Joinville Technological Center, Federal University of Santa Catarina, Joinville, SC 89219-600 Brazil
[b]Statistics Department, California Polytechnic State University, San Luis Obispo, CA 93407-0405

ABSTRACT

In a dual CubeSat system, to send data from the main satellite to the secondary one, and from the main satellite to earth or contrariwise, the transceivers must be chosen in order to achieve high transmission speeds and an optimal balance between efficiency and cost. A proposed experiment goes as follows: the primary satellite uses a spectrometer to gather data from the thermal infrared signal emitted by the target while hit by a laser beam originated from the main satellite; the data is then kept on hold in the main satellite until the next transmission window to the ground station opens and is later stored in-site and prepared for study and research. The proposed spacecraft to ground communication is based on the use of a low-cost UHF/VHF transceiver in the main satellite, used widely in CubeSat communication systems, and a hybrid antenna in the ground station facility and in the CubeSat as well, that is compatible with both frequencies and thus able to receive information sent from the main satellite. The main satellite must also have a receiver to be capable of commands to, and receiving telemetry data from the secondary satellite, which will send this information through the ZigBee (IEEE 802.15.4 RF) standard. This paper compares different transceivers for both satellites and ground station in order to guarantee the fastest and cheapest data transmission for the mission, and also calculates the data volume that will be sent during the entire mission in order to determine which communication equipment will maximize this mission's efficiency.

Keywords: Communication, Formation Flying, Infrared Spectroscopy, Directed Energy, Asteroid Composition

1. INTRODUCTION

1.1. CubeSat Standard

CubeSats are small satellites that are now routinely utilized by universities to integrate students with real projects involving orbital platforms. CubeSats are relatively low cost and most of their components are available as commercially-off-the-shelf (COTS) products. CubeSats are a class of nanosatellites that use a standard size and form factor,[1-3] where one unit, or 1U, measures 10x10x10 cm and a common weight limit of 3.3 kg; units may be combined to form larger structures, usually not surpassing ~28U. As the development of CubeSats has advanced into its own industry involving government, industry and academia, CubeSats now provide a cost effective platform for scientific research, new technology advances and cutting-edge mission concepts development, such as formation flying.

1.2. CubeSat Mission Context

This paper is related to a NASA Innovative Advanced Concepts (NIAC) grant, “Molecular Composition Analysis of Distant Targets”.[4] NIAC is a program that gives opportunities to visionary ideas that one day may be applied into NASA missions. Most of these ideas are to improve or create new aerospace concepts. The NIAC grant envisions using a laser to probe the molecular composition of space bodies such as asteroids, planets and other targets of the solar system. The laser is aboard a spacecraft that orbits the target, and heats a point on the target to the point of evaporation. A spectrometer aboard the spacecraft views the heated spot through the evaporated material. Infrared absorption spectra

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are then used to determine the molecular composition of the target. The method has been named Remote Laser-Evaporative Molecular Absorption (R-LEMA) spectroscopy. R-LEMA is currently being tested in the laboratory, as part of the NIAC Phase II grant.

In order to advance the Technology Readiness Level (TRL) of the R-LEMA system, a demonstration must be made in a relevant environment. A dual CubeSat experiment is proposed for low-Earth orbit, whereby one craft contains the R-LEMA system, and the other craft acts as a target. The two craft will fly in formation, so that the main craft R-LEMA module can remotely probe the composition of a blank in the target craft. This paper discusses the communication of the whole system, which is: how to transmit data from one CubeSat to another (CubeSats in formation flying) and also how to send and receive data from the main spacecraft with ground stations.

2. CUBESAT – GROUND STATION COMMUNICATION

2.1. Communication CubeSat-Ground Station

The communication system is vital for the entire mission, because it is the one that allows data and telemetry can be sent from the CubeSat to the ground station and vice versa, while also allowing the transmission of data and telemetry from one CubeSat to another, but that will be better discussed in the third topic of this paper.

The communication equipment choice is based on the NASA's document Small Spacecraft Technology State of Art.[5] This document argues that traditionally the communication between Earth and the spacecraft is based in the radio spectrum, mostly in the VHF (Very High Frequency) and UHF (Ultra High Frequency) bands, and for that reason, at a first moment, the ISIS VHF uplink/UHF downlink Full Duplex Transceiver is considered as the equipment responsible for communicating with the Earth. This is a reasonable choice since these bands are largely used in CubeSats, and also because the equipment, being a Transceiver, may transmit as well as receive data, what gives the advantage of physical space saving in CubeSat's interior.

For the hypothetical mission, parameters were set to define the geometry of the CubeSat's orbit such that it flights in low-earth orbit (LEO). Low earth orbits are characterized by their short range, high orbital velocity and non-geosynchronous nature.[6] With the orbital parameters defined in Table 1, the transmission window can be defined.

Table 1. Orbital Parameters.

Parameters	Value
Elevation	250 Km
Inclination	15 degrees

To calculate both velocity and period of a satellite, standard values for earth gravitational constant (μ_{Earth}) and for earth radius (R_{Earth}) are used,[7] and the mission altitude is already set (250 km). With these results, it is possible to find the time above the antenna for a single orbit, and this will be very important to find the data volume that can be sent or received by the CubeSat in one orbit. Since the spacecraft will maintain a constant altitude, the orbital speed will be also constant and given by Eq. (1)-(3).

$$v = \sqrt{\frac{\mu_{\text{earth}}}{r_{\text{mission}}}} = 7.759\,\frac{\text{km}}{\text{s}} \tag{1}$$

$$\mu_{\text{earth}} = 3.986 \text{ x } 10^5\,\frac{\text{km}^3}{\text{s}^2} \tag{2}$$

$$r_{\text{mission}} = \text{R}_{\text{earth}} + 250Km = 6621\,Km \tag{3}$$

The communication window for a satellite is the amount of time that a fixed ground command station can transmit to and receive signals from a satellite. The duration of this window is determined by the orbital parameters, and is defined as the length of time between Acquisition of Signal (AOS) and Loss of Signal (LOS)[6] as shown in Fig. 1. Since the velocity is known from the orbit, the period can be obtained, which is given by Eq. (4):

$$T = \frac{2\pi}{v} = 5361.63\,s = 1\,h\,49\,min \tag{4}$$

where T is the period and v is the velocity of Eq. 4. In order to obtain the time per pass over a determined point on Earth situated just under the orbit, Pythagoras theorem is used[8] as illustrated in Fig. 2.

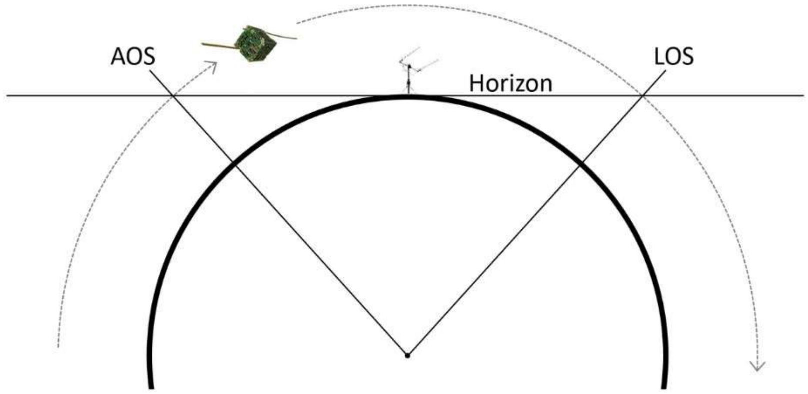

Figure 1. Communication Window in terms of AOS and LOS.

At this altitude, the angular radius of the mission is easily calculated by Eq. (5):

$$\alpha = \cos^{-1}\left(\frac{\mathrm{R}_{\mathrm{earth}}}{r_{\mathrm{mission}}}\right) = 15.8° \tag{5}$$

And so, to calculate the amount of time that the satellite is above the antenna's range per orbit we multiply the orbit period for two times α and divide for 360° as in Eq. (6):

$$Time\ above\ antenna\ per\ orbit = 5361.63 \cdot \frac{2 \cdot 15.8°}{360°} = 470.4855\ {}^{s}/_{orbit} \tag{6}$$

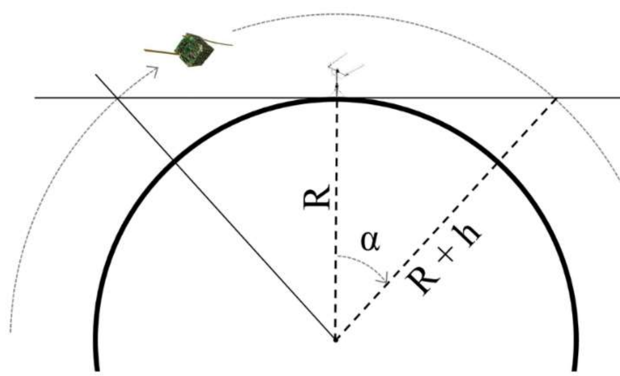

Figure 2. Orbital terms relevant to the calculation of communication window for a fixed ground station.

The ideal transmission window of about 7 minutes and 50 seconds occurs during an orbit when the spacecraft passes directly above a ground station. With such information it is possible to estimate the download/upload budget for the station pass based on the fabricant's information about the modules data rates, as shown in Tables 2 and 3, based on data transfer rates of the communication equipment aboard the CubeSat, and the ground station transceivers. It is possible to determine whether the chosen device for CubeSat-Ground station communication is apt to satisfy the needs of the mission. However, it should be noted that these estimates assume an ideal scenario with no data loss and full antenna coverage during each orbit; storage and metadata have not been taken into account either.

Table 3. Download data rates available with the equipment identified as compatible with the CubeSat design.

Data rate (bps)	Data per orbit (kB)	Data per day (MB)
9600	564,58	9,03
4800	282,29	4,51
2400	141,14	2,25
1200	70,56	1,12

Table 4. Upload data rates.

Data rate (bps)	Data per orbit (kB)	Data per day (MB)
9600	564,58	9,03
1200	70,56	1,12

2.2. Beacon

CubeSats with a long beacon are easier to track,[9] once it would be extremely difficult to locate a satellite using only short bursts of AX.25 encoded satellite telemetry. As well as CubeSat projects like CUTE-1[10], to this project an audible beacon is required in addition to an AX.25 beacon in order to help audibly acquire the satellite quickly and therefore obtain more usable time from the limited communication window.[6]

3. CUBESAT – CUBESAT COMMUNICATION

3.1. Orbital Model

Wireless communication systems are essential for the operation of CubeSat missions.[5] In a standard communication system applied to our formation flying mission, one link is established between two CubeSats and another link is established between the main CubeSat and the ground station. This section describes aspects of CubeSat-CubeSat communication.

As the operation requires the formation flying of two CubeSats to accomplish the mission, the need of a communication system between these is obvious. The system is based on the information trading between a primary CubeSat that sends commands to the secondary CubeSat and obtains data from it. The communication system between these two objects in orbit must be stable and reliable, as even small-scale failures can compromise the mission.

The experiment described considers a pair of CubeSats that must orbit together, with a distance between them to be defined in project. Since the distance between the CubeSats is critical to the operation of the communication modules, it is assumed that there are no situations during the lifespan of the equipment where the satellites are more distant than as intended in design; considerations about unexpected distancing and proposed troubleshooting are found in item four.

Following the very core ideas of CubeSat idealization[3], the physical characteristics of the equipment must always be the smallest and lightest possible. However, another requirement of the project is low energy consumption by the communication systems, especially in the specific experiment where a laser is used, which has the highest energy consumption of the system. Therefore, the project definitions are as follows: the communication apparatus must have reduced dimensions, low mass, low power consumption and a short operating distance between the primary and secondary CubeSats. The equipment of this link cannot have an external antenna to reduce the complexity of the system.

Table 5. Communication apparatus specifications comparison. References: Respective product's manufacturer issued user manuals/datasheets.[13,14]

Reference Name	Dimensions	Mass	Power Consumption	Frequency Band	Data Rate
ISIS High Data-rate S-band Transmitter	90 x 96 x 33 mm	300g	9.2W	2200-2290 MHz	3.4 Mbps (½ , ¼ and 1/8)
S-Band Transmitter for Pico and Nanosatellites	95 x 46 x 15 mm	75 g	4.95W	2200 - 2300 MHz	1.06 Mbit/s (maximum)
UHF downlink/VHF uplink Full Duplex Transceiver	90 x 96 x 15 mm	75g	0.48W (receiver only) 4 W (transmitter on)	Transmitter: 435 – 438 MHz Receiver: 145.8 – 146 MHz	1200, 2400, 4800 and 9600 bps
VHF downlink/UHF uplink Full Duplex Transceiver	96 x 90 x 15 mm	85g	0.2W (receiver only) 1.7 W (transmitter on)	Transmitter: 145.8 – 146 MHz Receiver: 435 - 438 MHz	Transmitter 9600 bps Receiver 1200bps
XBee-PRO® RF Modules	24.4 x 33 x 3 mm	<15g	0.825W	ISM 2.4 GHz	250,000 bps

Traditional communication systems between Earth and spacecraft are based in the radio spectrum, from about 30 MHz to 40 GHz. This can be used in spacecraft-to-spacecraft communication, sometimes referred to as Inter-Satellite Link (ISL).[5]

The Inter-Satellite Link is usually based on VHF and UHF radio frequencies (RF) with typical data rates of 1.2 kbps and 9.6 kbps, up to 3 Mbps on UHF band.[5] Also, S-band communication transmits considerably more data than UHF systems[5], although at a higher rate of energy consumption.

As the distance between the CubeSats must not exceed a few hundred meters in order to guarantee the success of the mission (data collection by the spectrometer), we opted for simpler systems, with greater data transmission volume, connection stability and energy efficiency. Therefore, it is possible to use frequencies of the radio spectrum that can transmit in the expected distance, without the need of oversizing the system. Since communication between CubeSats is constant, the most interesting technology among the state of the art will be the one which presents the lowest power consumption between traditional VHF / UHF systems.[11] Higher energy consumption in the experiment will lead to higher project costs regarding battery cells and solar panels. So the best solution found was a ZigBee (IEEE 802.15.4 RF) system that operates under ISM (Industrial, Scientific & Medical) 2.4 GHz frequency bands.[5]

In this experiment, the XBee-Pro® RF module was chosen[11-13] due to its specifications in accordance to the requirements of the mission. The manufacturer's specifications for the device, which are available in the manufacturer issued user manual[13], were considered safe and adaptable to the space environment, albeit yet to be tested in-flight. However, it should be noted that the study may be applied to any similar system that operates under the IEEE 802.15.4 RF / 2.4 GHz specification and is not limited to this manufacturer and/or model. The module has a signal range up to 1 mile (~1600 m) supplying the need, therefore, it consume much less energy than the usual systems.[13]

The experiment data obtained by the secondary CubeSat is transmitted to the primary while it waits for the next transmission window to send them to the ground station. So the transmission of large data packets between CubeSats is doable, since the communication between them is continuous. The uninterrupted connection between these objects in orbit is only possible thanks to the wireless module that consumes a very small, and thus sustainable, fraction of the system's energy, in addition to transmitting a quantity of data that is greater than necessary, at a distance determined by the operation of the experiment.[13]

3.2. Reliability

ZigBee (IEEE 802.15.4 RF) and UHF/VHF radio based communication systems, which are proposed to be used in this mission, are prone to present a large array of malfunctions and suffer from various environmental perturbations that may interfere in the quality and reliability of data being transmitted.[15] As such, minimizing the amount of information loss and/or corruption that can possibly occur during transmission within the CubeSats operational range is crucial to maximize the accuracy of data being received by the ground station, further cementing the trustworthiness of studies based upon this mission's results.

3.3. Relative Reliability

UHF/VHF communication has been the staple of CubeSat missions since its conception and radio based systems have well documented and successful flight history,[16,17] which serve as an increment to the system's overall reliability: once this mission's communication devices are entirely based upon commercially-off-the-shelf (COTS) components, the only sources for reliability data are the aforementioned documentation of past CubeSat missions and the fabricants themselves.[14]

ZigBee (IEEE 802.15.4 RF), on the other hand, has neither been extensively used nor documented enough that the assessment of its reliability can be corroborated by past missions. Inductively, we're left with the fabricant's data on the product,[13] which is satisfactory for operating temperature, range and network compatibility, but lacks additional information such as resistance to ionization and the like, once the XBee-Pro® RF module doesn't go through space-like environment tests prior to its commercialization.

Hard drives and other storage devices, while not the focus of the communication aspect of the mission, may be impacted by Single-Event Upsets (SEUs) and affect the data flux[18], so ways to shield such devices must also be taken into consideration.

4. MISSION DATA AND COMMUNICATION BUDGET

4.1. Data Sources

While the mission is still being defined, a preliminary list of equipment aboard the spacecraft gives an indication of the data volume that might be produced. Experiments will collect infrared spectra, being the primary payload of the spacecraft. Other data that will be relevant to the experiment, such as telemetry and state measurements, and the condition of the target craft, will also be sent to the ground for analysis of the experiment. An estimate of the data sources and volume for collection of one spectrum are listed in Table 6. A total volume of ~900 kbits is estimated for a single experiment, which includes primary payload data and auxiliary measurements. This preliminary estimate may grow, as auxiliary data are added to the data budget.

Table 6. Preliminary list of data sources and data format for experimental and telemetry data.

Subsystem	Format	Volume per Experiment
Laser	State Data	120 kbit
Spectrometer	240.000 bits (each experiment will record 5 spectra, with each being 6000 bytes)	240 kbit
Energy	PDU : 32 bytes (256 bits/value)	80 kbit
Attitude Control	Process data : 3 bytes (24 bits/measurement)	100 kbit
Thermal Control	Thermocouples: 3 bytes (24 bits/measurement)	120 kbit
Auxiliary Sensors	Laser: 3 bytes (24 bits/measurement) Magnetometer : 512 bytes (4096 bits) Camera (metadata) : 128 bytes (1024 bits/frame) Camera (image) : variable 300 kbytes/image	120 kbit
Target	Attitude Control data Thermal Control data Auxiliary data	120 kbit

4.2. Data Budget

The data produced by an experiment must be transmitted to the ground during any available communication windows. The total volume for a single experiment is estimated to be ~900 kbits. Transmission time for the estimated total data volume is listed in Table 7, for selected data rates.

Table 7. Estimated data volume and download times for un-compressed data at selected download rates.

For total volume of 900 kbits	1200 bps	9600 bps	3.4 Mbps
Download Time/Experiment	750 s	78 s	0.02 s
Experiments/Orbit	4	4	4
Download Time/Orbit	50 min	5 min	0.1 s

The download time is approximately 7.7 minutes per station, when the spacecraft passes directly above (Fig. 3). The mission scenario will likely include several experiments per orbit. For an orbit with four experiments, the approximate maximum volume of data to transmit per orbit is 456 kbytes. The conclusion is that data transfer opportunities must include higher-rate downlink to accommodate all data. Data compression would help alleviate the transmission budget. A high-rate downlink would also alleviate backlog.

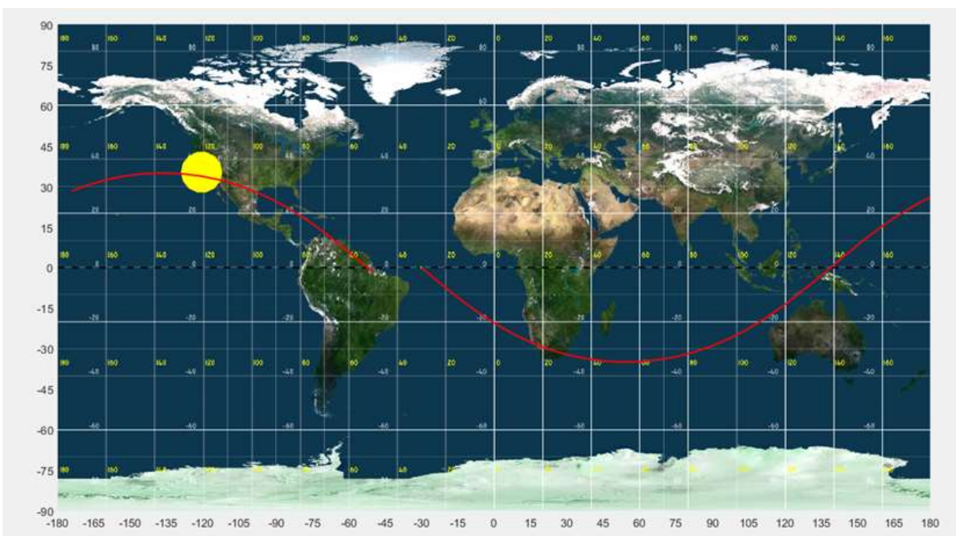

Figure 3. A simulated orbit, with the spacecraft passing over the ground station at Cal Poly SLO, CA.

5. CONCLUSIONS

5.1. Progress to Date

As of now, we have made a considerable amount of bibliographic revision and taken decisions about vital elements of the communication aspects of the mission based on peer-reviewed scientific data and specific empirical estimations. We are also modeling a MatLab simulation of the CubeSat's intended orbit in order to refine the results discussed above, especially in what concerns data budget.

5.2. Considerations for Additional Study

This paper is but a small, albeit vital, step in what ought to be done to make the communication systems of the mission fully operant, reliable and properly engineered to survive the harsh conditions of the flight: it is understood that we must reach further into advanced stages of analysis, simulation and testing to accomplish such operational standards. We therefore consider that it is needed to: expand the research of space environment effects on the Xbee modules and ways to shield them against it, define the exact communication architecture of the system and hone it, project realistic outcomes for the data budget based on simulation and testing, extend the understanding of data storing and apply its concepts to the project accordingly.

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