# Researching a Robust Communication Link for Cubesats: OPTOS, a new Approach

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***Abstract*—OPTOS is a Cubesat-based picosatellite that is been developed by INTA. The aim of this project is to provide an easy and low-cost access to space for those institutions and companies that can not afford the use of usual platforms. This is a new alternative way from the previous bigger and more expensive options to deal with small space missions. The fact that these little platforms are available in the future will promote that nowadays unfeasible projects will be able to come true, such as small microgravity experiments, observatories, material testing, etc. The advance in electronic miniaturization is expanding the possible applications that can be part of the Cubesat philosophy, which perhaps did not initially consider that complex mission could be implemented with limited resources, such as available power and volume. These payloads require reliable communication systems. From this point of view, an evolution is needed from the current technology used. OPTOS communication system tries to find a balance between limited available resources in Cubesat platform, i. e., inner dimensions and power, and having a reliable communication link. To achieve this goal OPTOS uses custom-made space-qualified equipment, deeply tested during an extensive trial campaign. To improve even more the communication link quality, OPTOS uses a non-amateur frequency band, reserved to space operations. This paper provides a general description of the OPTOS satellite and a detailed description of its communication link.**

***Keywords - Cubesats; communication system; transceiver; ground station; antennas.***

## I. INTRODUCTION

INTA is a Public Research Organization, located in Madrid, Spain, that has an extensive experience in space projects, and in all those technologies which can be applied to the aerospace field. It has the know-how and the facilities for almost every possible test related to space programs: antennas, environmental, electronics, solar, etc...

INTA has a new line of satellite pico-platforms that include state of the art technologies integrated in its subsystems, enabling high efficiency and low cost multipurpose satellite, which allows research applications at reasonable budgets. Its technological demonstrator, OPTOS, will be launched in 2011.

OPTOS is based on a Cubesat [1] 3U structure (10cm x 10cm x 30cm, and 3 kg) with improved payload capacity, system reliability and mission life time [2]. Figure 1. shows a 1:1 model of OPTOS with deployed antennas. The management and engineering processes follow the ECSS (European Cooperation for Space Standardization) standards, in order to assure good practices that improve the long term results. The standards were tailored to the project necessities.

Figure 1. OPTOS 1:1 Model

About the mission, OPTOS will be in a LEO (Low Earth Orbit), with a lifetime of 1 year. In this time, INTA hopes to qualify the platform and experiment with the 4 payloads in space. These payloads are:

- GMR (Giant Magneto-Resistance): Earth magnetic field measurements based on COTS (Commercial Off-The-Shelf) magnetic sensors,

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- ODM (OPTOS Dose Monitoring): dosimeters with commercial RadFETs, to monitor the total ionizing dose,
- FIBOS (Fiber Bragg Gratings for Optical Sensing): evaluate the feasibility of optical fiber sensors in space environment for temperature measurement, and
- APIS (Athermalized Panchromatic Imaging System): space qualification of specific glasses, the degradation under gamma rays and Earth observation.

The platform subsystems are:

- OBDH (On Board Data Handling): several units working together forming a distributed system, with different complexity degree and placed through the satellite,
- OBSW (On Board Software): control architecture of OPTOS satellite is distributed, following the hardware architecture,
- OBCOM (On Board Communication): each unit of the OBDH has an associated OBCOM module, small bidirectional terminals for optical wireless intrasatellite communication through a CAN bus,
- TCS (Thermal Control Subsystem): it is a passive subsystem, which uses paints and conductive materials on specific areas of the satellite for assuring operational temperatures,
- S&M (Structure and Mechanism): the external structure is mechanized to lodge the solar panels and one of the ADCS solar sensors, to give access to the satellite once the integration is finished and to keep free FOV for the camera and some solar sensors,
- EPS (Electrical Power Subsystem): supplies all the payloads and the platform subsystems,
- ADCS (Attitude Determination and Control Subsystem): with 2 sun sensors, 1 solar presence detector, 1 triple axis magnetometer, magneto-torques on three axes and 1 reaction wheel, and
- CS (Communication Subsystem): described in the next chapter.

Communications are essential for the success of the mission: the on-board transceiver and the ground station are both critical parts of the system. One of the main causes of unsuccessful Cubesats missions is related to the communication system, due to the use of non space-qualified electronic in the transceiver.

Section II deals with the detailed explanation of the different parts involved in the OPTOS communication subsystem. Section III describes the factors involved in the link budget and the limitations associated to each one. Section IV details both downlink and uplink link budget estimations. Finally, Section V deals with the conclusion and the future work lines derived from this project.

## II. OPTOS Communication Subsystem

CS is the most exigent subsystem in terms of budgets. On it lays the responsibility of the satellite to ground communications, the only way to know that the satellite is alive. The system has been designed with the aim of achieving at least a 3 dB margin in the final link budget result. The link budget is an estimation that considers all the gains and losses that the signal suffers along the complete path between the transmitter and the receiver, and the added noise effect that degrades the signal quality. This margin, between the estimated $E_b/N_0$ (bit energy over noise spectral density) at the demodulator output and the theoretical required value, allows to accomplish a certain BER (Bit Error Rate), in downlink and uplink as well. BER is a quality factor that also depends on the modulation scheme used [3].

To strengthen the communications INTA has chosen a professional on-board transceiver made by Thales Alenia Space, with an RF (Radio-Frequency) ASIC (Application Specific Integrated Circuit) designed for space [4]. The transceiver works half-duplex at 402 MHz and provides a maximum transmitted power of 25.5 dBm. A phase modulation is used, direct with Manchester data for downlink at variable rate, 5 kbps nominal, and with a BPSK (Binary Phase-Shift Keying) 16 kHz subcarrier with NRZ (Non Return to Zero) data for uplink at 4 kbps. This scheme is recommended by ESA (European Space Agency) ECSS-E-ST-50-05C standard, as well as other subsystems of OPTOS project follows the ESA recommendations. The transceiver provides housekeeping signaling that offers better control over the signal acquisition process and the transceiver health status.

Two transceiver models have been manufactured, an electrical model and a flight model. One will serve as a test model for ground working and the other will be launched. Both models are tested with the corresponding models of the rest of the communication equipment: onboard antennas, onboard computer, onboard software, ground antenna, ground equipment and ground software. Figure 2. shows the uncovered RF side of the transceiver EM, where a 4:1 splitter, Tx/Rx switch, Tx and Rx RF chains and a PLL can be appreciated. The ASIC and the current regulators are in the other side of the transceiver.

OPTOS Ground Station is located at INTA facilities. The functions of the ground station are to receive/transmit information from/to the satellite, manage the platform and the scientific payloads and distribute the data to the scientific partners. A LDRM (Low Data Rate Modem), an ELTA transceiver, has been chosen, which provides automatic signal search and lock functionality, ASB, fading, noise and Doppler effect simulation [5].

Besides, in order to improve the quality of the link, a LNA (Low Noise Amplifier) and a HPA (High Power Amplifier) are used in the downlink and uplink chain, respectively. For the data processing stage, an ELTA FS (Frame Synchronizer) has been chosen, capable of using synchronization word, Reed-Solomon encoding/decoding and uplink randomization.

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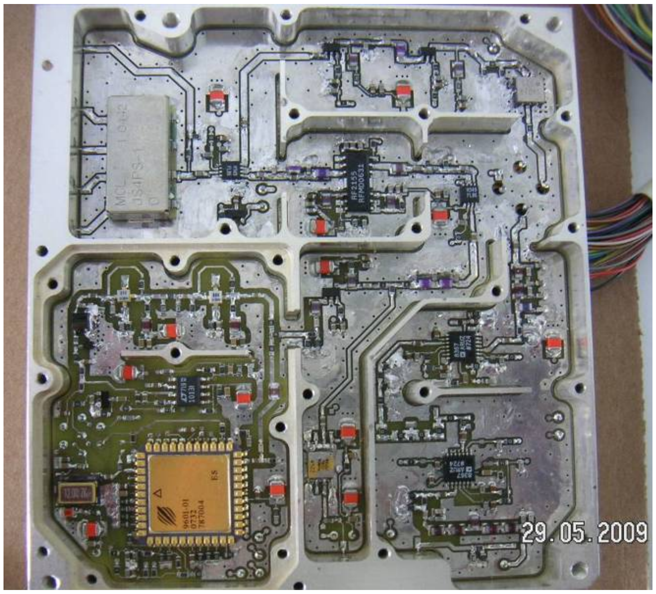


Figure 2. Uncovered on-board transceiver EM

Regarding the antennas, the on-board antenna consists of four λ/4 monopoles with circular polarization, placed in each of the four lateral sides, with a deployment system [6]. The Ground Station antenna, located at INTA facilities, is formed by an array of four Yagi antennas with circular polarization and an elevation over azimuth positioner [7]. Figure 3. shows the ground antenna lying on the elevation over azimuth positioner on top of a 3 m mast, placed on the flat roof of the Space Programmes and Space Sciences Department building.

Figure 3. Ground station antenna

INTA has developed the software to control, operate and distribute data to the scientific users. Also has made a custom Communication Protocol, with FEC (Forward Error Correction) Reed-Solomon, and ARQ (Automatic Repeat Request) scheme.

## III. Factors to be Considered in the Link Budget

Link Budget [8] determines the feasibility of a possible bidirectional communication link between OPTOS and the ground station considered with the link margin adequate to transmit and receive the required data volume with the established bit rate attending to mission and orbital characteristics (orbital height, shape, eccentricity and contacts number, time duration and satellite-ground station relative configuration), and the communication architecture.

Due to the limited communication capacity because of the limited electrical power (therefore limited RF power) that the small effective surface of solar cells could supply, it's a challenge to attempt to communicate with such a small and light satellite.

The possibility to establish the link and the available link margin depends on:

- Orbit: range and duration of each contact satellite-ground station
- Frequency band
- RF Power available
- Bandwidth occupied and Bit Rate
- Ground Station and satellite performance: EIRP and G/T

The main objective of the link budget is to evaluate the possibility of communication fixing these parameters according to technical possibilities and the constraints imposed by the rest of subsystems and the mission.

### *A. Orbit*

OPTOS shall describe a LEO helio-synchronous polar orbit. Different orbital heights have been considered to analyze which one gives the best conditions to carry out OPTOS and its payloads mission. Two different orbital heights have been simulated for the link budget: 670 km and 817 km. The launch has been established on 2011. The final orbit depends on the launcher, that is still to be confirmed.

The Ground Segment has been installed at INTA (40.4ºN, 3.46ºW). The frequency band considered is UHF (402MHz). At this frequency the ground station is an easier and cheaper solution than higher frequencies.

The contact time and the communication capacity establish the maximum data rate that OPTOS system is able to communicate in downlink and uplink.

The orbit shall be a circular one, so the orbital eccentricity is practically negligible and it will not be considered differences in range and contact time between apogee and perigee, and so, the bit rate shall be fixed for all the contacts.

Contact times have been simulated using STK software developed by AGI. OPTOS will have at least three contacts daily according to the considered elevations to each case (obviously considering contact with lower elevations the number of contacts per day increases but the communication is more difficult due to other effects like multipath signals). The total contact time per day should be at least 28.95 minutes.

The transceiver bit rates have been set to 5 kbps for downlink and 4 kbps for uplink. There is an option to change the downlink bit rate via TC (Telecommand), but in order to simplify the subsystem testing phase, this option will not be used till the satellite mission ending. The data budget estimation, removing protocol headers and taking into account a TM (Telemetry) /TC ratio of 90/10, is: 725.37 kB/day for TM and 98.12 kB/day for TC. The total data estimation is 823.49 kB/day.

### *B. Frequency*

The frequency band selection has been based in several factors:

- Link budget results: UHF band (402 MHz) have better results than higher frequencies
- Complexity and physical characteristics of on-board antennas and transceiver design
- ITU Frequency Coordination requirement with other countries and type of service available for the satellite related with its mission

From the antennas point of view, UHF band is more preferred than VHF because the former is compounded of shorter monopoles than the latter, and therefore more suitable for OPTOS requirements. From the design complexity point of view, transceiver and antenna are similar in both frequency bands. The double band UHF/VHF has been rejected based in the transceiver first feasibility studies. These determine that the double band requires a design that doesn't fulfil with power consumption, volume and mass requirements.

### *C. Power available*

The low power available in the satellite is a strong handicap to fulfil OPTOS communication requirement, above all to complete the downlink with the required link margin to assure the communication.

The maximum power that the EPS could supply to the platform and payloads is estimated in 6 W. So, calculations of Link Budget must consider that the whole transceiver unit is supplied with 2.73 W to be shared between both electrical and RF components. Considering the subsystem design, 0.5 W are available at HPA output as RF Output Power.

### *D. Bandwidth occupied and Bit Rate*

The bandwidth occupied and the bit rate are related each other by means of the spectral efficiency of the modulation used. Spectral efficiency refers to the information rate that can be transmitted over a given bandwidth, measured in (bit/s)/Hz. The spectral efficiency is 0.7 (bit/s)/Hz in the uplink (BPSK) and 0.5 (bit/s)/Hz in the downlink (Manchester).

The Bit Rate is fixed at 4 kbps in the uplink, and it is variable in the downlink, but during the mission it will be fixed at 5 kbps. At the mission conclusion, the Bit Rate can be modified to test the Link Budget margin. The rest of downlink parameters: orbit, output power, antenna gain, et al. can not be modified after the launch.

### *E. Ground Station and satellite performance*

TABLE I. summarizes the main parameters of both the ground station and satellite communications.

Antenna gain, cable losses, amplifier maximum power and receiver noise figure have been measured at INTA RF laboratories. The GS (Ground Station) amplifier maximum power is 100 W, but, as the link budget shows, there is not need to use it at its maximum. Besides this, and in order to reduce the electromagnetic radiation in the GS surroundings, a value of 5 W is used, high enough to get the expected link budget margin.

The values of antenna noise temperature considered have been simulated through numerical integration at the worst case following ITU-R P.372-8 radio noise recommendation ($F_{sky}$[artificial] = 11 dB at 400 MHz). Preliminary GS antenna noise measures have been done in situ and the results indicate that the antenna noise temperature is significantly lower than the previously estimated, but until more precise measures are taken, worst case antenna temperature value has been considered to the link budget calculations.

TABLE I. COMMUNICATION PARAMETERS

| Parameter | *Ground Station* | *Satellite* |
|---|---|---|
| Antenna Gain | 18.0 dBi | -3.0 dBi |
| Transceiver Output Power | 37.0 dBm | 25.6 dBm |
| $L_{Tx}$ | 0.89 dB | 0.30 dB |
| $L_{Rx}$ | 0.37 dB | 0.30 dB |
| $F_{RX}$ | 7 dB | 1.6 dB |
| System Noise Temperature | 34.1 dBK | 26.2 dBK |
| EIRP | 24.1 dBW | -7.8 dBW |
| G/T | -16.5 dB/K | -29.5 dB/K |

The system let to improve the ground station performance, if subsequent phases require it, adding antennas and obtaining a more complex configuration with an Antennas Array System. And so, improving the gain of the Antenna System in 2-3dB duplicating the number of antenna elements.

The antennas configuration on-board the satellite depends on the working frequency band selected and the surface available in the satellite to fix the antennas before the launch and during the mission. A four quarter-wave monopole configuration has been chosen due to OPTOS structure. The antenna has a quasi-omnidirectional radiation pattern to assure the link independently of the relative orientation of the satellite.

 

## IV. LINK BUDGET ESTIMATIONS

The link budget estimations have been done with two different orbital heights: 670 km and 817 km. From now on, the results correspond to the worst case height, 817 km, which provides the tightest link margin.

In the next subsections, the downlink and uplink link budget estimations are presented in TABLE II. and TABLE III. respectively. The more significant parameters used are explained below:

- $L_{FS}$: Free space losses between satellite and ground station antennas, following ITU-R P.525-2.
- $L_P$: Worst case polarization losses, depending on satellite attitude.
- $P_{RX}$: Signal power received at the LNA input.
- $P_{NOISE}$: Noise power received at the LNA input.
- $C/N_0$: Carrier over noise spectral density at the LNA input.
- $C''/N_0$: Signal power over noise spectral density at the demodulator input.
- $E_b/N_0$ available: Bit energy over noise spectral density at the demodulator input, before Coding Gain.
- Required BER: Link quality factor from the OPTOS requirement specification.
- Required $E_b/N_0$: Bit energy over noise spectral density necessary to achieve the required BER, depending on the modulation used.
- Coding Gain: Digital gain related to the coding scheme used, which improves the resulting BER.
- Link Margin: Difference between the available $E_b/N_0$ and the required $E_b/N_0$, considering the increase due to Coding Gain.

Attenuation by atmospheric gases is not applicable at this low frequency in accordance with ITU-R P.676-8. For the same reason, attenuation by rain, clouds and fog has not been considered according to ITU-R P.838-3 and ITU-R P.840-4. Ionospheric scintillation exceptionally occurs in the middle latitudes, in line with ITU-R P.531-10, so it also has not been taken into account.

The minimum elevation for the link budget estimations is 10°, with a maximum distance of 2402 km.

The ground antenna includes a device that allows the polarization to be changed according to the satellite attitude. Making use of the received power marker at ground station, the system will automatically switch the circular polarization in the opposite direction when the maximum power drops off more than 3 dB. Therefore, the losses associated with this lack of polarization alignment between satellite and ground station could be 3 dB at worst case.

Both $P_{RX}$ and $P_{NOISE}$ permit to calculate the $C/N_0$ at the LNA input. In order to estimate the $E_b/N_0$ available at the demodulator input and compare it with the required one for the specified BER, it is necessary to calculate the carrier drop when modulating the signal and see the real signal level over noise density, $C''/N_0$. To do this, the residual carrier power $C'/N_0$ has to be subtracted from the $C/N_0$ in order to get the $C''/N_0$. Then, the $E_b/N_0$ results from taking away the binary rate $R_b$ and the demodulator losses (around 2 dB in both cases).

### A. Downlink

In TABLE II. the more relevant downlink budget parameters are listed, together with its estimated values.

The margin is so tight because of the limited power available in the on-board transceiver and the high ground station antenna noise temperature estimated through numerical integration.

This value of 3.1 dB is calculated in worst case situation at the beginning of the pass. After that moment, as the time passes and the distance decreases, the free space losses are lower, reaching the minimum at the middle of the communication window. So, the margin increases and there is the possibility to increase the transmission bit rate to improve the throughput of the link.

TABLE II. DOWNLINK LINK BUDGET

| **Parameter** | ***Estimated value*** |
|---|---|
| $L_{FS}$ | 152.1 dB |
| $L_P$ | 3 dB |
| $P_{RX}$ | -145.3 dBW |
| $P_{NOISE}$ | -194.5 dBW/Hz |
| Modulation | PM (Manchester SP-L) |
| Bit Rate | 5 kbps (nominal) |
| $C/N_0$ | 49.3 dBHz |
| $C''/ N_0$ | 48.6 dBHz |
| $E_b/N_0$ available | 9.7 dB |
| Required BER | $10^{-5}$ |
| Required $E_b/N_0$ | 9.6 dB |
| Coding Gain | 3 dB |
| Link Margin | 3.1 dB |

### B. Uplink

In TABLE III. the more relevant uplink budget parameters and its estimated values are listed.

The 18.8 dB margin is higher than in the downlink case, mainly due to the greater transmission power and the lower system noise temperature caused by the reduced noise that the antenna receives in the space. As the uplink bit rate is fixed by the transceiver, there is no possibility to improve the uplink throughput increasing the bit rate. So, the only choice is to reduce the transmitted power in the ground station, reducing in this way the electromagnetic radiation in the surroundings.

TABLE III. UPLINK LINK BUDGET

| **Parameter** | ***Estimated value*** |
|---|---|

| Parameter | *Estimated value* |
|---|---|
| $L_{FS}$ | 152.1 dB |
| $L_P$ | 3 dB |
| $P_{RX}$ | -134.3 dBW |
| $P_{NOISE}$ | -202.4 dBW/Hz |
| Modulation | PM/BPSK (NRZ) |
| Bit Rate | 4 kbps (fixed) |
| $C/N_0$ | 68.1 dBHz |
| $C''/ N_0$ | 67.9 dBHz |
| $E_b/N_0$ available | 25.4 dB |
| Required BER | $10^{-5}$ |
| Required $E_b/N_0$ | 9.6 dB |
| Coding Gain | 3 dB |
| Link Margin | 18.8 dB |

## V. CONCLUSION AND FUTURE WORK

This paper has presented the OPTOS CubeSat, with particular stress upon its communications subsystem. OPTOS communication subsystem uses non amateur space reserved frequency band. The subsystem is composed of custom elements purpose-made: on-board transceiver unit, ground segment equipment, and both on board and ground antennas.

The link quality depends on certain factors, which have been analyzed in order to reach a balance between limited available resources on board in such a small satellite and having a robust communication link. The critical point is the downlink received power at the ground station antenna, because of the limited transceiver output power and the antenna omnidirectional radiation pattern on board. Even with these limitations, an acceptable link budget margin has been achieved.

The values of Eb/No margin obtained are always above 3 dB for worst orbital case. This positive margin, together with the ARQ protocol, result in a robust communication link.

It would be interesting to fully characterize the electromagnetic noise in the place that hosts the ground station. This possibility will be considered as an activity in next phase.

In future developments, in order to enhance the signal level at the ground station input ($P_{Rx}$ at the downlink), some communication parameters are feasible to be changed:

- $P_{TX}$: On-board transceiver transmission power could be improved, despite the picosatellite limitations due to the restricted available power.
- $G_{Rx}$: The ground station gain could be improved using an antenna with better gain or an antenna system disposing them in array to enhance its behaviour.
- $F_{Rx}$: The ground station system noise figure (or its system noise temperature) would be better using a receiver with lower noise figure, decreasing the transmission line losses and optimizing the devices set up.
- $L_{Tx}$: Using shorter and better cables in the ground segment configuration to reduce the cable losses.


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