Development of an experimental telemetry system

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***Abstract*—This article presents the design and implementation of a communications system to receive information about the status, height, speed, temperature or any other type of variable of interest from vehicles such as balloons or experimental rockets. In a first iteration, the system was designed to achieve transmission distances in the order of dozens kilometers but leaving some margin to extend the operating range to up to 100 km in line of sight. At the beginning of the project different factors such as the use of a frequency band suitable for this type of applications, the modulation scheme to use and a data protocol were analyzed. Subsequently, the most appropriate commercial devices to implement each of the system blocks were selected. With these components a first prototype of the telemetry board was built and the necessary tests to verify the correct performance of it were conducted. Finally, the design and implementation of the flight hardware was carried out and the final tests that fully validated the proposed design were performed.**

I. Introduction

Within communications, telemetry is a widely used technique for the measurement of variables, either manually or automatically, in remote locations, difficult to access or having hostile environmental conditions. In general, telemetry systems are of the wireless type.

The main objective of telemetry systems is to measure physical and chemical variables, to know the state of processes and systems remotely. It is because of this, that we can find them in a wide variety of applications and processes from multiple areas like vehicular, space, biomedical and industrial.

A telemetry system usually consists of a transducer as an input device, a transmitter, a transmission medium (either wired or wireless), a receiver, signal processing devices, and finally some means for data storing or visualization. It should be noted that the modules that comprise it may vary depending on the application or the transmission medium. In addition, several current commercial devices integrate different modules of this scheme simplifying the design. A diagram of a typical telemetry system can be seen in Fig. 1.

The system proposed in this work allows reception of information about height, acceleration, angular velocity, temperature or any other type of variable of interest of vehicles such as balloons or experimental rockets. Specifically, the telemetry system is intended to be used in an experimental rocket project of the Center for Aerospace Technology (CTA) of the Faculty of Engineering of the National University of La Plata. The project consists of the development of a suborbital probe rocket as a platform for research and development of

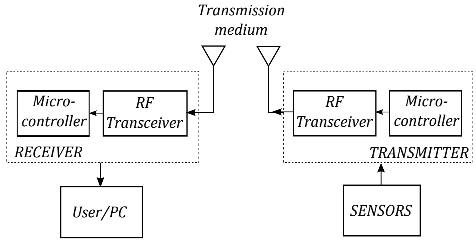

Fig. 1. Diagram of a typical telemetry system.

aerospace systems and studies of upper-atmosphere phenomena. The need for a communications module in each of the experimental rockets of the program drove the design and development of this telemetry link. The ultimate goal of the system is to receive and store data of the vehicle status and all the measurements that its instruments generate at a maximum height of 100 km above sea level and with a transmission rate that would not exceed 100 kbps, this last parameter depending on the quantity and nature of the variables to measure. It should be noted that for the first stages of the project the height reached by the rockets will not exceed 2 km. Therefore, the telemetry system was designed to achieve transmission distances of that order but leaving margin to extend it to up to 100 km (the distance required in the final stage of the project). The way to achieve this performance is to improve the reception chain with Low Noise Amplifiers (LNA) and High-Gain Antennas for example.

The following are some of the requirements for the first vehicles of the project:

- *Data to be transmitted during flight:* The variables of interest during flight can be many and consequently result in a complex telemetry system. The most important parameters to be measured are the acceleration and angular velocity of the rocket on the x, y and z axes.
- *Data to be transmitted prior to launch:* In the moments prior to the launch, data transmission is also very important. Either in descending or ascending direction, to receive measurements or to send some commands to the board.
- *Design of the flight board:* To accommodate the electronic boards and everything related to it, the available space is cylindrical, of 10 cm in diameter by 30 cm in height, located at the top of the rocket (nose cone). Because of

these space constraints and the large acceleration values at which the components will be subjected during launch, it was thought of a circular design mounted transversely to the longitudinal axis of the rocket.

- *Antenna Design:* The transmitting antenna must be as omnidirectional as possible since the rocket will rotate all the time on its own axis (in order to stabilize its trajectory) and that should not affect the transmission. The simplest alternative to carry out this function is monopole antenna [1]. For the frequency band commonly used in this type of applications (420-470 MHz) the monopole antenna should have a length of 17 cm. This allows it to be housed on the nose cone of the rocket reducing the signal attenuation produced by the rocket itself. In [13] we can find other designs for transmission antennas and the comparison between them.

It should be noted that the correct functioning of the RF link is of vital importance to obtain the measurements in real time. This is necessary since in many cases it will not be possible to recover the rocket and the extraction of the data stored by the board.

The rest of the paper is organized as follows. In Section 2 we analyze different factors related to the communication link. Section 3 describes the commercial devices selected to implement each of the system blocks. Section 4 shows the first prototype of the telemetry board and the tests performed to verify the correct performance of the selected chips. Section 5 presents the design and construction of the final flight board. Section 6 details the link tests and results obtained. Finally, Section 7 details the conclusions.

II. Link analysis

To begin with the design of the system it was necessary to set some parameters as the transmission frequency and type of modulation. A complete analysis of the link was then carried out to evaluate feasibility and to know the theoretical limits of it.

A. Frequency band

The 433 MHz band was used for the design proposed in this work. This decision was made considering two fundamental criteria: the compatibility of a large number of commercial RF transceivers with this range of the spectrum and the possibility of emitting considerable power levels without the need of complex permits or legal authorizations. Within this band there are different types of services that overlap and cause interference, therefore some care must be taken when implementing the link.

B. Modulation scheme

In order to implement the system with a simple and robust receiver, to avoid synchronization problems and to lower costs, we opted for a non-coherent modulation, as is usual in this type of applications. Digital FSK (Frequency-shift keying) modulation is the most used modulation for this class of systems and it can be carried out with commercial components of low cost and so that was the chosen option.

C. Link budget

The link budget allows us to ensure that the receiver has at its input, the minimum signal power to achieve a certain reliability and estimated error rate. Note that in this section the link budget is performed for a link distance of 100 km. Remember that for the first stages of the project the height reached by the rockets is an order of magnitude lower and therefore in this stages there is an additional margin of 20 dB for the link budget.

1) Free space propagation: In a system such as the one presented in this work, where the link is made between a rocket several kilometers in height and an earth station with its antenna pointing practically towards the rocket, we can assume that there is no interference by reflected waves and also there will always be line of sight between the transmitter and the receiver. With these assumptions we can use a free space transmission model and apply the Friis equation

$$P_{tel} = 32.4 + 20\log(f) + 20\log(D) \tag{1}$$

In Equation 1 we can see that the free space transmission loss (P_{tel}) depends on the frequency of operation f (measured in megahertz) and the distance of the link D (measured in kilometers). Replacing in the previous equation with the estimated values for the present link, where the maximum height that would reach the rocket is around 100 km, we obtain:

$$P_{tel} = 32.4 + 20\log(433) + 20\log(100) = 125\text{dB} \tag{2}$$

2) Availability and Fade Margin FM: Assuming a model containing only transmission losses in the free space may prove too ideal for a practical link. Therefore we must add an additional margin to contemplate all possible additional losses that may appear. This margin is called the fade margin (FM). Considering an availability (percentage of time in which the link operates without interruptions) of 97$\%$ recommended by the ITU for this type of systems [2], an operating frequency in the 433 MHz band and a maximum transmission distance of 100 km, we obtain that the necessary FM is approximately 3.35 dB [3].

Considering that the maximum permissible Equivalent Isotropically Radiated Power (EIRP) in this band is 10.7 dBm and that the transmission losses will be the free space path plus the fading margin of 3.35 dB recommended, we can calculate the power that will receive our ground receiver (P_{rx}) with an estimated gain for receiver antenna (G_{rx}) of 6 dB as indicated by Equation 3.

$$P_{rx} = \text{EIRP} + G_{rx} - P_{tel} - \text{FM} \geq \text{sensibility} \tag{3}$$

Replacing the values for our link in the above equation, the estimated received power is -111 dBm. This power value is at the limit of the minimum that many of the commercial devices need to be able to operate correctly (approximately -110 dBm). Therefore, the link was theoretically feasible taking the necessary care that the commercial device chosen for reception has a sensitivity greater than the calculated value.

Also note that with the additional margin of 20 dB for the first stages of the project, we should reach the first objectives without problems.

III. Commercial solutions

The work aims to develop a low cost and fast response telemetry system without losing the reliability of the link. To achieve this objective the system was implemented with commercial devices. Commercial solutions chosen to implement each of the modules of the telemetry system are discussed in detail below.

A. Transducers

In a telemetry system, the transducers involved are used to design the communication link since the number and nature of them fixes the amount and speed of data to transmit. In this work, the variables that are measured are: acceleration in x, y, z axes (principally in the z axis, if this is the longitudinal axis of the vehicle), angular velocity in the x, y, z axes, altitude of the ship and temperature of the printed circuit board.

1) Accelerometer/Gyroscope: The MPU-6050 of INVENSENSE [4],[5] is an Inertial Measurement Unit (IMU) that combines a three axes accelerometer and a three axes gyroscope giving a total of six degrees of freedom. Both the gyroscope and accelerometer have 16-bit digital outputs and can be configured to have different full-scale range for each magnitude.

2) Barometer: The MS5607-02BA03 is the latest generation of TE Conectivity barometric pressure sensor [6]. This chip was selected to measure the altitude of the vehicle with a resolution of 20 cm in a range of 1 kPa at 120 kPa.

3) Thermistor: To sense temperature on the telemetry board the MCP9700 of Microchip [7] was chosen. The SOT-23-3 device package allows accurate measurement of temperature on the circuit printed board.

B. RF Transceiver

The transceiver selected for the system was the Texas Instruments CC1200 [8]. It is capable of reaching a maximum of 1250 kbps transmission rate and the output power is configurable to up to 14 dBm. The user can choose different modulation schemes (FSK, MSK, OOK) as well as different frequency bands (164-190 MHz, 410-475 MHz and 820-950 MHz) with a great adjacent channel rejection.

C. Flash memory

In order to store the samples collected by the sensors to be backed up for any inconvenience of the RF module, an additional memory was included in the board. Thus the N25Q256A flash memory of MICRON TECHNOLOGY [9] was selected. This memory has an SPI bus and has a storage capacity of 256 Mbits.

D. Microcontroller

In a telemetry system the microcontroller must have the computing capacity and enough peripherals to process and transfer all the variables of interest. An ARM-Cortex-M3 microcontroller named LPC1769 from NXP Semiconductors [10] was chosen for this project, because it is recommended for applications requiring a high level of integration and low power dissipation. The device reaches CPU frequencies of up to 120 MHz, which makes it a high-speed version within the LPC1700 family. In addition, it has a wide variety of peripherals such as SPI, I2C, UARTs, required for this application.

IV. Development model

The Development Model board (DM) is the first prototype designed and built to validate the correct performance of the chips selected for the proposed telemetry system. This board was implemented with different commercial modules containing the same chips that would be used in the final flight design. This allowed shortening the development times.

The DM board was implemented in a single layer design, taking care of the dimensions of tracks and holes in order to be able to manufacture it without having to resort to a PCB manufacturing company, which would increase the cost.

The basic function of the DM is to take samples of acceleration and angular velocity using the accelerometer/gyroscope module, send them to the microcontroller for conditioning and finally transmit them through the RF module at the same time as they are stored in flash memory as a backup.

A. Main components

This section presents a brief description of the main modules of the board.

1) Stick LPCXPRESSO 1769: This module is the core of the board. It contains the microcontroller chosen for the project, the LPC1769, along with all the necessary components for its operation. It also contains a USB interface to easily debug programs developed through a PC.

2) GY-521: The GY-521 board contains the accelerometer/gyroscope (MPU-6050), a voltage regulator, a crystal and the all the passive components necessary for the correct operation of the chip .

3) N25Q256A flash memory: This surface mount flash memory was placed on the DM board.

4) EM-CC1200: This evaluation module of Texas Instruments integrates the RF transceiver necessary for data transmission and reception (the CC1200) together with the antenna suitable for the frequency band to be used, a crystal oscillator and all the passive components required for the correct operation of the chip.

B. Prototype construction

The PCB was made in a single layer design. This allowed the board to have a simple design, thus enabling it to be 'homemade' manufacture. In the bottom layer of the DM board the surface mount devices (SMD) were housed and

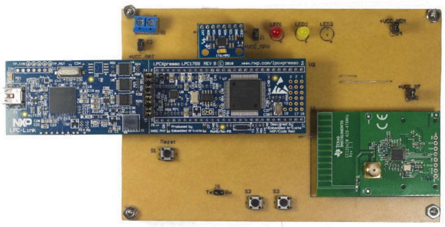

Fig. 2. Top view of the DM board with all its modules connected.

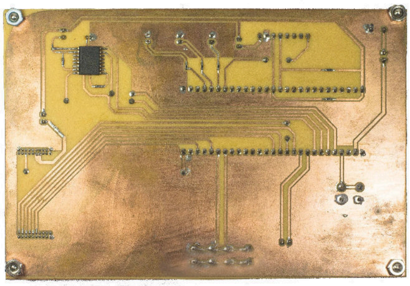

Fig. 3. DM board bottom view.

almost all of the routing was performed. On the top layer, the sockets for the modules and all the Through-Hole components (like terminal blocks, jumpers, LEDs and push-buttons) were mounted. Also, on the top layer, connections which were not possible to be made on the bottom layer were carried out. The manufactured and fully assembled prototype can be seen in the Fig. 2 and Fig. 3.

C. Software development and link tests

Once the DM board was fabricated, tests were performed in order to optimize the link performance. It began by transmitting data at short distances (a few meters) and with transmission rates below 50 kbps in order to improve the software of the board until finding the optimal configuration for each of its modules. With the passage of tests, the link range and the transmission speed were increased until reaching 1000 meters in line of sight with bit rates in the order of 100 kbps.

1) Operating scheme: To implement the DM board software, a free Integrated Development Environment (IDE) of NXP based on Eclipse was used, using C language and debugging the programs through the USB interface included in the LPCXpresso stick. A main program was implemented to acquire acceleration and angular velocity samples of the MPU-6050, to condition them through the microcontroller of the stick LPCXpresso and to transmit them in real time with the RF transceiver CC1200 at the same time that they were stored in the flash memory as backup.

2) Lab tests: Before carrying out the field tests, laboratory tests (at transmission distances of a few meters) were carried out between the DM board and one of the Texas Instruments transceivers evaluation boards (TI) acquired. Using the software provided by that manufacturer [11], the CC1200 was configured with different values as it's shown in the following list:

- Modulation scheme: 2-FSK, 4-FSK, 2-GFSK, 4-GFSK and MSK.
- Frequency deviation: 10 to 100 kHz.
- Transmission rate: 25 kbps, 50 kbps and 100 kbps.
- Packet handling: packet length, headers, error-detecting and error-correcting codes.
- Output power: -40 to 10 dBm.

In [12] we can find similar tests performed to achieve the optimum configuration of other commercial transceivers. After the first stage of testing and analysis of the different configurations (comparing the number of errors, transmission rate and sensitivity in the receiver obtained with each one), the configuration shown in Table I was chosen to be loaded in the final software of the DM board.

TABLE I
FINAL CONFIGURATION OF THE TRANSCEIVER

Parameter	Value
Modulation scheme	4-GFSK
Frequency deviation	50 kHz
Transmission rate	100 kbps
Packet length	60 bytes
Preamble	3 bytes
Sync word	32 bits
CRC	2 bytes
Error-correcting code	Enable
Output power	1 dBm

Fig. 4. 1 km link test developed in the hippodrome of La Plata city between the DM board and one of the TI evaluation boards (capture of Google Earth).

3) Outdoor tests: Link tests were performed using the DM board as the transmitter and one of the Texas evaluation boards as the receptor. The tests were performed at one kilometer distance with line of sight between boards (see Fig. 4) and at 100 kbps data rate. Series of 5000 packets were transmitted in a lapse of time of 1 minute and with output powers of less than 1 mW. The results obtained were very satisfactory, achieving a packet error rate less than 1%.

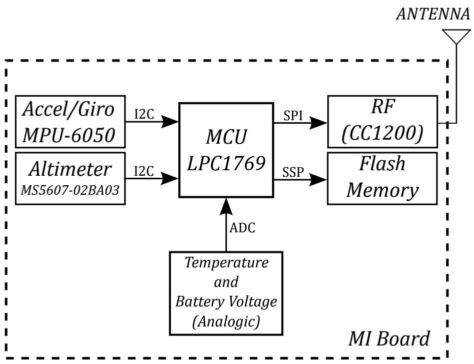

Fig. 5. EM board block diagram.

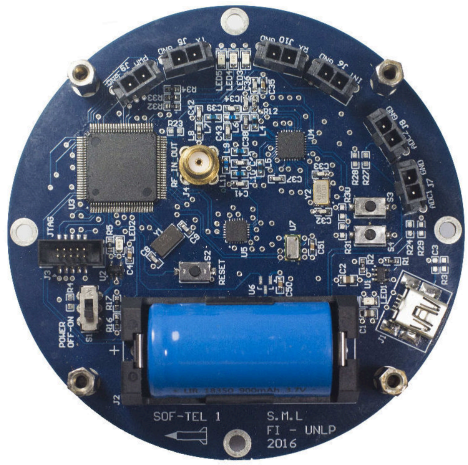

Fig. 6. Top view of finished EM board.

V. Engineering model

The Engineering Model board (EM) is the final flight board capable of performing data transmission from a rocket or experimental probe balloon. The EM board consists of different main blocks conformed of all chips detailed throughout the work. Fig. 5 shows a block diagram of the board where the interface used for communication with each module is indicated in each case.

A. Special design considerations

For the design of the EM board, a series of restrictions imposed by the system of which it will be a part of must be respected. The following list shows the main points that were considered prior to the actual design:

- Circular board shape to mount it directly on the body of the rocket from which it will transmit the telemetry.
- 3 mm diameter holes to fix the board to the rocket.
- Robust connectors to withstand significant mechanical stress.
- Connectors and holes near the edges of the board.
- Accelerometer/gyroscope mounted in the center of the board to simplify the processing of received data.
- Preferably surface mount (SMD) components to optimize available space and take advantage of the good RF qualities that they possess.
- Use of power and ground planes of each component of the board, dividing it into sectors that are fed independently.

B. Board construction

For the printed circuit of the EM, due to the quantity and complexity of the connections to be made, we opted for a four layers design . Two signal layers (enough to mount and connect all the components), a ground plane and a power plane. The dielectric material chosen to separate the signal layers from the power and ground planes was FR4 of dielectric constant $\varepsilon_r \simeq 4$. To interconnect the different layers, vias were used with a suitable diameter for the type of components used and the tracks density of the board.

The width of the tracks in general is 8 mils with a separation between them of 16 mils in the optimum case. This size is due to the dimensions of the pins of main chips such as CC1200 and LPC1769. For the connection of decoupling capacitors and other lines with greater power consumption, a track width of 15 mils was used, reducing the impedance of the same. On the other hand, lines such as those involved in the RF stage need to have a controlled impedance (50 Ω). To achieve this impedance, a width track of 19 mils was used. This was calculated with the LineCalc tool of the software Advanced Design System (ADS) .

To power the board it was decided to include a Li-Ion 18350 rechargeable 900 mAh battery housed on the printed circuit, thus achieving independence from other systems present in the rocket or vehicle containing it. Before the selection of the battery, an analysis of the total consumption of the board was carried out. With this analysis it was estimated that the maximun current supplied by battery (with the transmitter at 10 dBm and 100 kbps) would not exceed 100 mA. So, with the Li-Ion 18350 battery, the board will have 9 hours of autonomy. This is more than enough to transmit data during the flight of the rocket and in pre-launch testing. The built and fully assembled board can be seen in Fig. 6.

VI. Link tests and results

Two link tests were performed to fully validate the design of the EM board. In both cases, one of the evaluation boards of Texas Instruments was used to receive the data transmitted by the EM board and send them to a PC for real-time visualization and subsequent processing. As explained throughout this paper, in the first stages of the project the height achieved by the rockets will not exceed 2 km. Considering this and assuming that we will always have line of sight between the rocket and the earth station, it was decided to perform the following link tests to validate the operation of the telemetry system. Note that for these validation tests a commercial receiver and a low-gain antenna (monopole antenna) were used.

A. 1 km test

A 1 km link test was carried out under the same test conditions detailed in Section IV-C3. Batches of 5000 packets

TABLE III
3 KM TEST RESULTS

Field	Value
Link range	3 km
Output power	4 dBm
Transmission rate	100 kbps
Average received power	-90 dBm
Packets received	4999
Packets lost	1
Packets OK	4992
Packets NOK	7
Packet error rate	0.16%

TABLE II
1 KM TEST RESULTS

Field	Value
Link range	1.02 km
Output power	1 dBm
Transmission rate	100 kbps
Average received power	-90 dBm
Packets received	5000
Packets lost	0
Packets OK	5000
Packets NOK	0
Packet error rate	0%

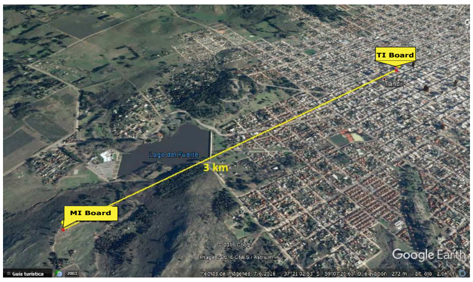

Fig. 7. 3 km link test developed in the city of Tandil (capture of Google Earth).

were transmitted with the EM board and were received with one of the evaluation boards of Texas Instruments. Fig. 4 illustrates the boards positions during test. The transmitted packets contained samples taken by different sensors of the board such as angular velocity, acceleration, altitude, battery voltage and board temperature. The results of the test are listed in Table II.

B. 3 km test

In this test, performed in the city of Tandil, the boards were located with a separation of 3 km as shown in Fig. 7. The packets were transmitted with the EM board from a hill in the outskirts of the city and were received with one of the Texas Instruments boards located on the terrace of a building in the town. As in the previous test, batches of 5000 packets were transmitted with the data taken by the sensors of the board.

The results were very satisfactory and are detailed in Table III.

This test confirmed the correct performance of the board and the possibility of further extending the link since the transceiver was not configured with the maximum allowed power (10 dBm approx.). Also the receiver and antennas used were not optimal. Future lines of work contemplate improvements to the receiver and in particular the receiving antenna. It will them be possible to perform link tests at a greater distance (approaching 100 km in line of sight) and in real conditions, either with a balloon or experimental rocket.

VII. CONCLUSION

A telemetry system capable of transmitting in real time different variables of interest from a rocket or experimental balloon was designed and developed. This system is able to to operate at distances and transmission rates higher than other commercial devices and with a very low transmission power and battery consumption.

In principle, the most convenient frequency bands were investigated both from a legal and functional point of view. After this first phase, commercial solutions were chosen for the implementation of the system. Once the main components of the system were selected, a first prototype of telemetry board (DM board) was developed. With this prototype, different validation tests and software development tasks were carried out in parallel with the design and manufacture of the final flight board (EM board). After the construction of the latter, its operation was verified transmitting data with a rate of 100 kbps and over distances in the order of 3000 m.

The results obtained during the tests were very satisfactory and fully validated the proposed design.

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