# Successful Development of Portable Didactic Satellite for Training and Research in Satellite Technology*

Esaú Vicente-Vivas[1], C. Álvarez-Bernal[2], E. A. Jiménez[3], Z. Carrizales[3], C.A. Sánchez[3], J.R. Córdova[4], R. Alva[3], M.A. García[3] and G. Islas[3]

[1]Instituto de Ingeniería, UNAM, Cd. Universitaria Coyoacan, 04510, México DF.
[2]Instituto Tecnológico de Sonora, Campus Guaymas, Sonora, México
[3]Student, FI-UNAM, Cd. Universitaria, Coyoacan, 04510, México DF.
[4]Student, Posgrado Ingeniería, UNAM, Cd. Universitaria, Coyoacan, 04510, México DF.

evv@unam.mx, calvarez@itson.mx, factore8@hotmail.com, zairalilian@yahoo.com.mx, carlos_ss@msn.com, roro_send@hotmail.com, imatrion@yahoo.com.mx, janorius@yahoo.com.mx, jcordovaa@iingen.unam.mx

**Abstract.** This paper depicts the global specifications and the successful results for a cost-effective system developed for training purposes in the small satellite technology field. The didactic satellite subsystems were fully designed, manufactured and tested at the Institute of Engineering UNAM. Information about intelligent subsystems for the portable didactic satellite, its operations software as well as successful results obtained in laboratory operations for the first system prototype are exposed in this paper. In addition, the planned collaborative work in the field with Instituto Tecnológico de Sonora is mentioned.

**Keywords:** didactic satellite, operational prototype, portable laboratory equipment, training system, cost-effective technology.

## 1 Introduction

Mexico has developed in the past a couple of small satellites projects, and currently is developing a couple more of them. Those projects are very important not only to bridge the enormous technological gap with industrialized countries, but also to launch a domestic satellite development and research program associated to the future Mexican Space Agency (MEXSA). The MEXSA could take us in the medium and long term to generate our own Remote Sensing and Communications satellites, according to the needs of the country. However, to conduct such a line of work, it is required the formation, qualification, and training of human resources in these technological areas.

In accordance with our experience, the development of an experimental satellite in our country requires of 4 to 8 years of work, depending on the obtained financial

* Project 52297 financed by CONACYT



Received 18/03/09
Accepted 27/04/09
Final version 07/05/09

support, as well as on the magnitude of the technological and scientific objectives.

We have also detected that this type of projects allows the participation of 25 to 200 people according to the challenges and magnitude of the technological demands aimed by the satellite mission. Considering the cost of this type of projects (half million to 5 million US dollars) the ratio between the amount of participant personnel versus project cost is very low. In addition, if we consider how young Mexican University people become attracted and motivated by satellite and space projects, it is observed an extremely low efficiency in the rows of participation and training of new human resources in this field. By the way, this technology arena is related with the possibility to generate alternative solutions to national security problems from our country. That scenario took us to the development of the portable didactic satellite (PDS).

In this way, our group has successfully developed a cost-effective training system in small satellite technology employing commercial-off-the-shelf (COTS) parts as well as electronic components from automotive and services industries, Fig. 1. The system is affordable enough to be used in laboratories with the intention to offer attractive, fast, and versatile training practices and courses in satellite technology and related fields. Our goal is to use the system in High Schools, Technological Institutes and Universities, with the intention of approaching young people to the world of space applications, Science and Technology.

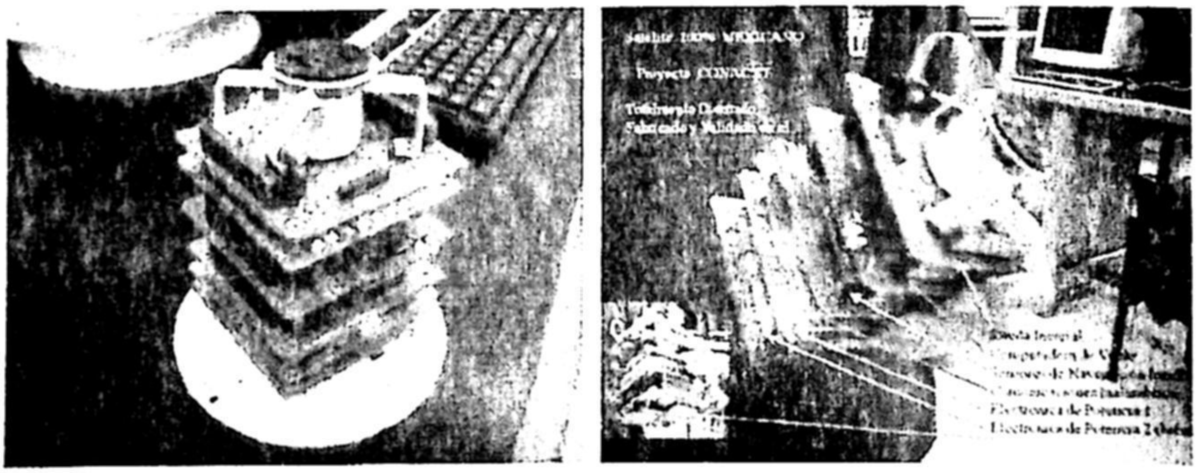


**Fig. 1.** Developed Mexican portable didactic satellite showing its architecture based in subsystem modularity.

To accomplish a cost-effective PDS its print circuit boards (PCB) were designed and manufactured in two layers only; the power subsystem considers the use of flexible solar panels, rechargeable batteries and an external battery charger; 1-wire sensors were preferred; and the PDS structure was chosen according with cost-effective commercial available products. In addition, several cost-effective auxiliary interfaces such as the orientation determination sensors, serial and USB expansion ports, as well as expansion cards for user defined interfaces are integrated in the PDS. In this way, the PDS is perceived as a friendly device with growing capabilities.

The PDS was projected to be useful in research laboratories to develop new solutions and modules for real satellite subsystems. In this sense, research in fields such as three axis stabilization, digital communications, satellite sensors, power systems, payload validation, flight computers, navigation autonomy, and satellite constellations will be addressed with the support of this laboratory satellite tool.

It must be mentioned that commercial availability of similar products to the PDS is rarely seen in the global market. Right now the only commercial educative satellite product detected by the authors is the Eyassat educational system developed initially by the US Air Force and later commercialized by Colorado Satellite Services, [1]. Besides, we found that very few institutions have developed their own satellite prototype to accomplish laboratory research in distributed space systems, as the case of the Israel Institute of Technology [2] and the US Naval Academy Satellite Laboratory with its "LABsat" experimental hardware, [3].

The Eyassat basic equipment starts at 8,000 dollars. However, this price is difficult to be afforded in developing countries. This is why the Mexican PDS was developed to be offered for a cost under 3,000 US dollars in order to be attractive for different schools, universities, and so on. This goal shaped the main characteristics of the PDS in order to achieve a cost-effective satellite training tool.

It is also important to highlight that we took advantage of previous experiences in space projects, [4], [5] and [6], to fast track this project.

In this way, the paper describes the PDS prototype and its successful operations in laboratory. The paper presents information for every PDS subsystem as well as software information for both the PDS and its ground station. In addition, some innovative PDS operating modes are described, among them: a reaction wheel based stabilization system and software that allows 3D visualization in a laptop by means of monitoring the PDS maneuvers performed by the user.

The PDS prototype was developed under CONACYT project 52979. Right now the satellite prototype is being employed for demonstrative purposes before federal government agencies and some Universities. The goal is to show the technological capabilities from our group to develop not only satellite training systems, but also to develop real small picosatellites and nanosatellites according to the "cubesat" standard developed in 1999 by Dr. Robert Twiggs from Stanford University in USA. In addition, the successful results obtained with the PDS are being employed to launch new and real small satellite projects in México. The new satellite projects will take advantage of experiences and technology from PDS subsystems presented in this paper. The work developed for real small satellites will be presented in future papers.

## 2 PDS Architecture

The satellite training system (STS) is basically formed by the PDS, operations software, and executable software for personal computers. The PDS contains operations control software to carry out, among other functions: 1) digital communications with a personal computer, that performs as the Ground Station (GS) for Telemetry acquisition and Command Shipment, 2) task delivery requested by the GS, 3) acquisition of telemetry from PDS subsystems, 4) telemetry pack up for wireless transmission, 5) protocols for GS communications, 6) real time operations with the didactic satellite, etc.

The STS has a cylindrical shape of 12 cm in diameter and 17 cm as maximum height. It also includes the ground station Software that runs in a PC and carries out the functions of telemetry acquisition and command transmission to the PDS, Fig. 1. Besides, this software allows the uploading of new operations software to the PDS by wireless means.

The PDS architecture was basically defined by its flight computer dimensions, which were fixed according with real dimensions of Picosatellites, [7], [8], [9], [10], and [11]. Therefore, the STS PCB size is 8.5cm x 8.5cm, Fig. 1. The PCB architecture allows the satellite boards to be assembled in tandem, Fig. 1. The complementary PDS subsystems are: Power, communications, sensors, inertial wheel stabilization and magnetic torquer coil stabilization.

## 3 Flight Computer Subsystem

The PDS has a single board flight computer, Fig. 2, which integrates lateral connectors in a bus fashion to interconnect cards in tandem. The electrical connector offers the required mechanical ties among printed circuit boards. In addition, each PCB contains screw holes at each one of the corners, which allow screwing the whole printed board array to the PDS structure.

With the bus type connectors its electrical signals are available for all the PDS cards, thus it is possible the card interconnection without caring about the order of them. Therefore, the order mentioned in the next paragraphs gives just an order to the article writing. Besides, it is important to notice out that all the bus type connectors in the cards are male type in their top part, whereas the bottom side looks like a wire-wrap connector. This allows the interconnection of cards either by the top or the bottom side.

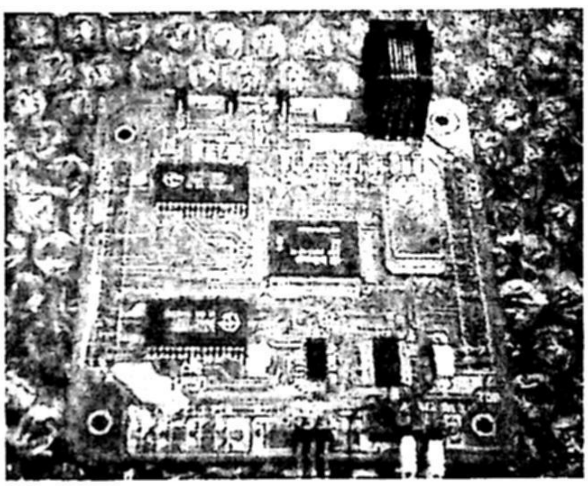


Fig. 2. PDS flight computer

The PDS single board computer is built around the 16 bit RISC SAB80C166 Siemens processor, industrial version, with extended temperature, 40 Mhz oscillator, 256 kb of RAM memory where the PDS operations program is loaded, hardware for automatic uploading of new programs to the computer and a total of 5 serial ports. The lasts support full-duplex asynchronous communication up to 625 Kbaud and half-duplex synchronous communication up to 2.5 Mbaud. The synchronous mode is employed in serial port So1 to gain access to a USB port on one side, and on the other side serial port So2 allows the communication with a 32 Mb block of Flash Memory. The Flash Memory allows to store diverse PDS telemetry data from the PDS.

On the other hand, the 100-pin SAB80C166 microcontroller internally contains important resources as follows: a watch dog timer, an interrupt controller, some 16-bit timers, 10-channel 10-bit A/D converters, two serial channels and several 16 bits I/O ports, with a total of 76 I/O lines.

The SAB80C166 allows the upload of new programs in external RAM memory, however it is required to control several electrical signals in accordance with specific feedback responses from the processor. For this purpose a small PIC microcontroller was integrated in the PCB which is also connected to the communications channel with the Ground Station. In this way, when the GS software sends the "new program download" command to the PDS, the PIC16F877 microcontroller takes over the control of the SAB processor to achieve and supervise the uploading process.

Regarding the software development for the SAB80C166 it was written in standard "C" language, programs were compiled using the BSO Tasking family of tools for the SAB80C166 microcontroller.

## 4 Power Subsystem

The second PDS subsystem is the intelligent power subsystem (IPS) integrated in 2 PCBs, Fig. 3. The first one contains 4 AA-sized lithium rechargeable batteries and electronics that admit the batteries to be recharged by means of solar panels or from an external battery charger. The second board integrates a PIC microcontroller, solid state switches, voltage regulators, DC/DC converters as well a latch-up protection circuitry.

In this way, the IPS constitutes a simple, small, and economic power subsystem.

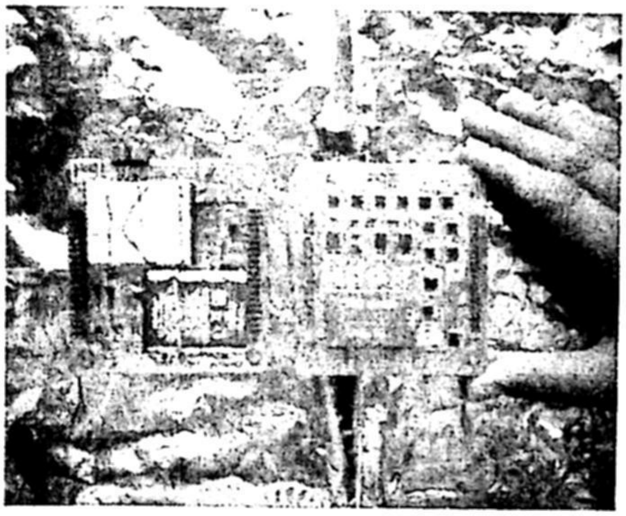


**Fig. 3.** PDS power subsystem.

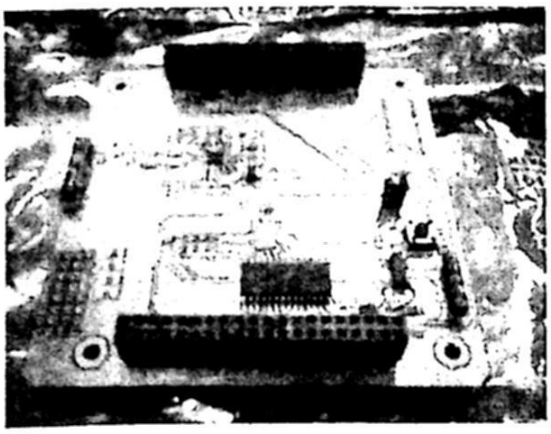
## 5 Wireless Communications Subsystem

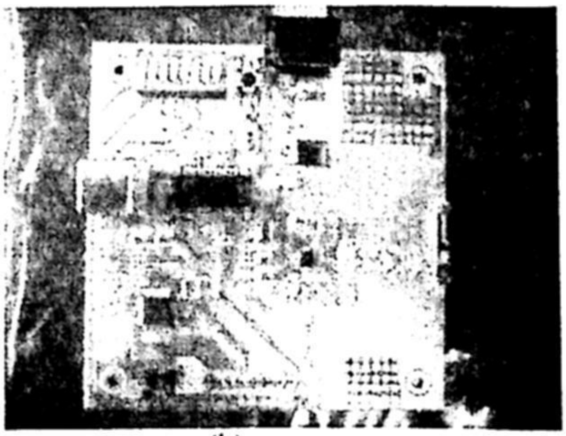
The third card constitutes the intelligent PIC based wireless communications system.

This subsystem confers a great operating versatility to the didactic satellite.

The STS communications subsystem consists of 2 wireless cards. One for the PDS and a second one for a laptop that performs as the GS, Fig. 4a and Fig. 4b.

The communications wireless card for the PDS, Fig. 4a, has the followings characteristics: it receives the radiofrequency signal through an antenna, then it passes to a filtering stage; the RF signal is taken to the RF chip CC2500 to generate serial data in SPI format; the 18F2321 PIC device controls the RF chip; the PIC device converts synchronous data into asynchronous data; finally, data are delivered to the flight computer.





(a) (b)

**Fig. 4.** The STS communications subsystem, a) for PDS and, (b) for ground station.

On the other hand, the wireless communications card for GS, Fig. 4b, allows any laptop computer to interact by wireless means with PDS. Its main components are a USB interface chip that generates an asynchronous serial output signal, a PIC device to control the serial data transmission and reception among laptop and flight computer, an RF chip CC2500 for wireless transmission in the 2.4 GHz band and a surface mount antennae. In addition, the PIC is interfaced to digital microswitches to choose among 255 RF communication channels configurations to avoid data collisions when multiple RF cards are employed together. This means that up to 255 different PDS equipments can be operated together without interferences between each other.

## 6 Platform and Inertial Navigation Sensors

The fourth PIC based intelligent card integrates the satellite inertial navigation sensors, Fig. 5. Although, each one of the described cards has at least a pair of local platform sensors (current and temperature) this card integrates three 1-axis gyroscopes as well as three 1-axis accelerometers. In addition it contains a digital compass. The referred navigation sensors are extremely useful to provide real-time PDS navigation data which is employed at the ground station to render 3-D virtual navigation graphics. The navigation acquisition mode is requested by command, and allows the GS software to generate 3D real time animations in connection with the satellite manipulation generated by the user in the laboratory environment.

The PDS employs the 1490 digital compass from Robson Company. It is a solid-state Hall effect cheap device, 12 pin component, with cylindrical shape and requires 5 V supply. When rotated it senses the position of the four cardinal points on a compass, North, South, East and West. As well as the intermediate directions: North East, North West, South East, and South West.

It has to be noticed that most of the PDS sensors are 1-wire technology, they were selected to significantly reduce the number of traveling signals through the PDS bus. The 1-wire sensors let the microcontroller, by means of only two wires, to access an important amount of sensors. This contrasts with conventional sensors, which require two wires to connect every included sensor.

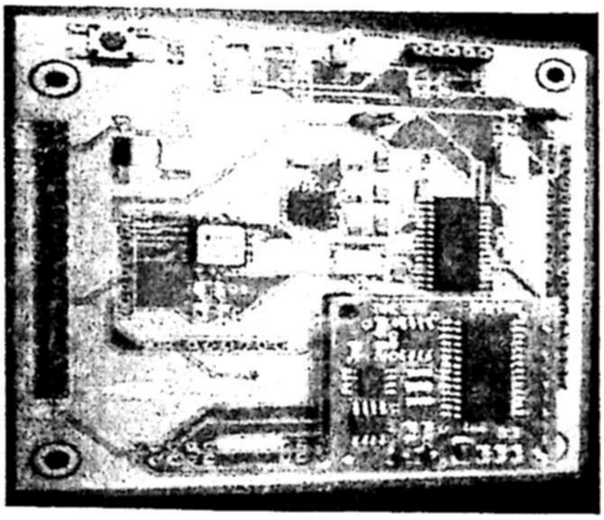


**Fig. 5.** PDS inertial navigation sensors.

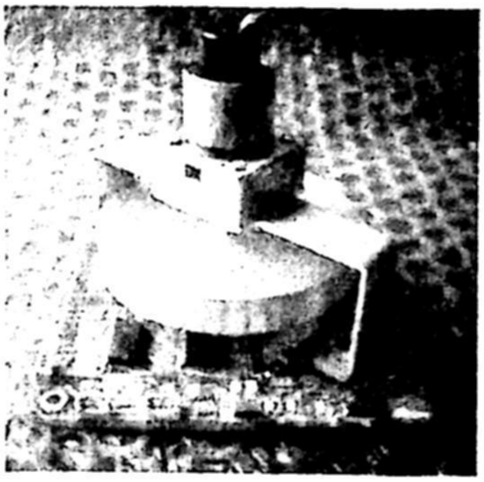


**Fig. 6.** PDS momentum wheel stabilization subsystem.

## 7 Stabilization Subsystem

The reaction/momentum wheels are attractive because they apply a torque to a single axis of a spacecraft by adding or removing energy from the reaction/momentum wheel (flywheel), causing it to react by rotating.

By maintaining flywheel rotation, called momentum, a single axis of a spacecraft can be stabilized. Consequently, several reaction/momentum wheels can be used to provide full three-axis attitude control and stability in a space vehicle, [1]. However, for automatic PDS maneuvering and automatic stabilization purposes the system includes only one reaction/momentum wheel.

For those reasons the PDS includes an intelligent satellite stabilization hardware to allow satellite maneuvering demonstration capabilities, Fig. 6. This eventually would conduct to elaborate tasks such as payload pointing towards specific targets and more important, to allow the users of the educative system to learn and understand the use of this important satellite resource.

The exposed system constitutes an intelligent stabilization module therefore it includes a dedicated microcontroller to perform both stabilizations tasks and communications with the flight computer.

In this sense, the PDS allows the emulation of a satellite stabilization system by means of a reaction/momentum wheel. It will allow the study and experimentation of PDS behavior when changes or control is applied in its system actuators. That experience and knowledge is expected to take us to the design and exploration of different small satellite stabilization control schemes.

The stabilization subsystem (SS) is made up of a flywheel driven by a DC motor and a set of six magnetic torquing coils, two different coils (coarse and fine) for each one of the ES structure axis. Three coils apply a coarse momentum while the other three provide fine momentum forces. The dedicated control is given by a PIC18F4431 microcontroller that is connected through serial port with the flight computer, this microcontroller unit receives and processes commands from the flight computer. The command and protocol software was inherited from software developed in our laboratory for a 50 Kg microsatellite mission, [7]. The chosen PIC device has enough resources and capabilities to accomplish the tasks for this subsystem. In addition, SS contains the electronic control interfaces between the microcontroller and the active stabilization actuators. They are composed by an H bridge for the motor (TA7291S from Toshiba) and six further H bridges (3 L293DD integrated circuits from ST Electronics) driven as hardware interface to control the magnetic torquing coils.

In order to carry out the motor control it was added a 16 pulses per round-trip encoder mounted in the motor along with the flywheel. This serves as feedback to the microcontroller. Besides, in case the motor could become obstructed the system has an overcurrent circuit to protect both the motor and its driving H bridge. It also has a set of LEDs that indicate the behavior of control signals applied to the stabilization actuators.

The stabilization card lodges the DC motor, an inertial mass located in the rotation axis of the motor and related electronics.

The reaction wheel is controlled both in open and closed loop configurations. When the PDS is hanged by a string from the ceiling, the last operating mode enables PDS visible and controlled movements that are quickly observed by the users.

In addition, the PDS contains a real time PDS virtual follow-on mode. This mode started by command from the ground station software forces the PDS to continuously capture information from inertial navigation sensors (3 axis gyroscope, 3 axis accelerometer and digital compass) and then transfers the acquired data by wireless means to the GS software. Then the GS software automatically and continuously draws 3D images according to the inertial navigation sensors data.

Both previous visual and interactive modes allow the user to see and easily understand the concepts of satellite supervision and satellite navigation sensors in a friendly manner.

# 8 PDS Operations

It is necessary to point out that under laboratory validation testing the didactic satellite is suspended in the laboratory ceiling by means of a string, as shown in Fig. 7.

Once in a suspended position, a digital command can be sent through the communications system, and then received by the PDS computer, then, as an answer action, it will actuate the motor in the rotation direction and at the RPMs indicated by the command. Under these circumstances, the didactic satellite experiences reaction forces that generate the PDS physical movements. This process allows the user to carry out several dynamic experiments for satellite stabilization control in a cost-effective fashion.

**Fig. 7.** The PDS under validation in laboratory.

# 9 PDS Structural Subsystem

The PDS structure is composed by a cheap commercially available cylindrical container manufactured with plastic, Fig. 7 and Fig. 8. When it was considered the manufacture cost of the structure, the manufacture time and the acquisition of materials, it was decided to go for the commercial cylindrical container. In addition, the last solution allows the PDS to be integrated at a lower cost through the reduction of manual labor. The chosen structure is light, cost-effective and shapes the PDS to render a satellite appearance. Once the full PDS PCBs are plugged together, the stack is fixed inside the plastic structure with screws.

**Fig. 8.** PDS structural subsystem.

## 10 PDS Operations Software

PDS operation software is distributed into every satellite subsystem, however, the PDS flight computer allows the coordinated control required by the PDS in order to execute operating functions such as subsystem powering, telemetry gathering, stabilization tasks, wireless operations, command reception, telemetry transmission and so on.

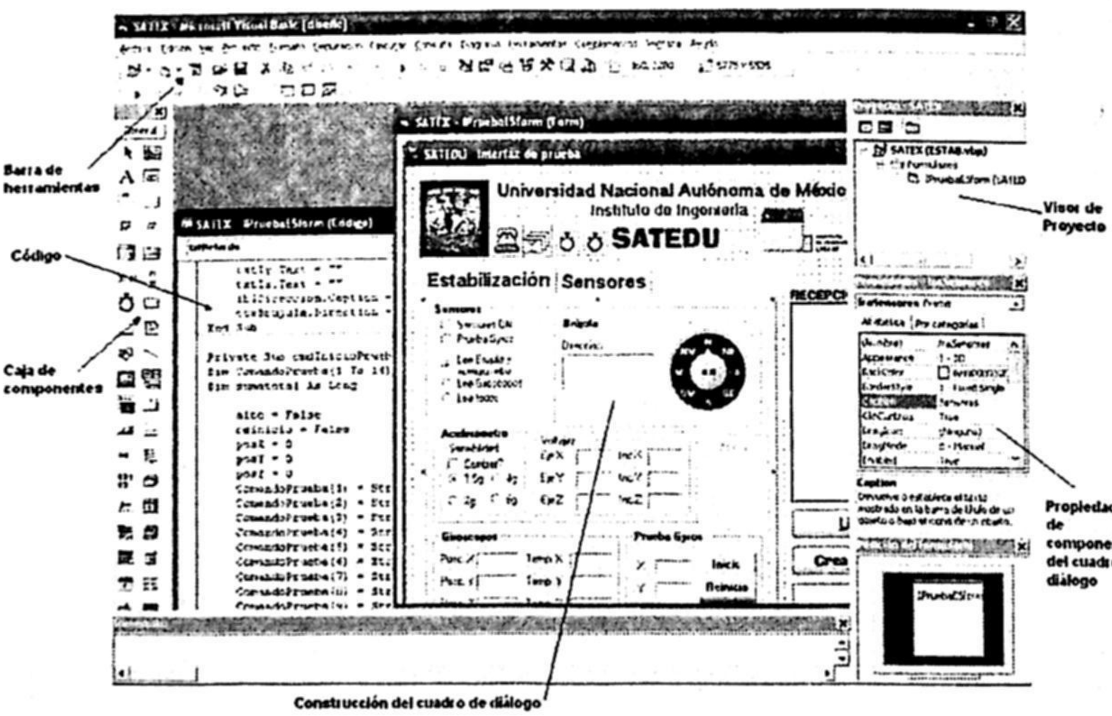
## 11 Ground Station Software

The GS software executes in personal computers and interacts with the PDS software to achieve both the demonstration and the training functions of the didactic satellite system, Fig. 9. In fact, great part of the friendship attributes for the whole STS system (simplicity and clarity of use) are generated by this software.

The software has several functions, such as those employed to control small satellites launched into space orbit, among them: 1) Immediate answer commands, 2) Telemetry request commands, 3) Real time telemetry requests to allow on-line PDS supervision with the help of 3D animations, 4) Satellite stabilization control commands, etc.

## 12 Projected Work for the Project

The whole STS software will be recorded in a compact disk (CD) which will also contain the user and the operations manuals. For these reasons, the STS final version will consist only of the PDS and a CD. This is the system we expect to share with educative institutions from our country.



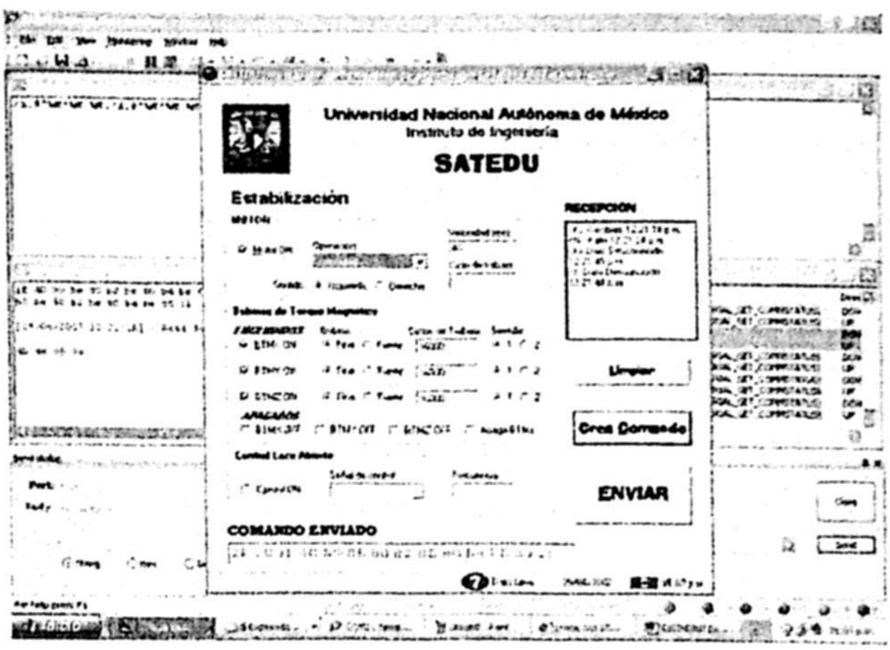



**Fig. 9.** Software developed for the ground station.

In addition to the system that is described in this article, a laboratory practice and other educative manuals will be elaborated later with the support of the "Instituto Tecnológico de Sonora (ITSON)" in Guaymas, México. This will allow carrying out training practices with the satellite system in a simple and friendly way, in order to teach the satellite system operation to the users. These manuals will be carefully elaborated to emphasize the clarity of concepts, as well as the progressive transference of information, besides reinforcing the learned knowledge, the questioning of treated subjects, as well as the comparison of learned concepts with the operation of commercial small satellite systems. In addition the patent acquisition as well as the possible PDS commercialization will be managed both by UNAM and ITSON Guaymas. The organization, development, and implantation of this learning and training methodology as well as future results will appear in later publications.

## 13 Concluding Remarks

We have presented the global architecture and operations characteristics for a portable and cost-effective system to train human resources in the field of small satellite technology. The first prototype is fully operative and its successful operations are based on 15 years of experience and work in the area. The PDS also considers the attraction of young people from our country for the satellite and the space fields. On the other hand, we expect the project will be affordable for many Institutes, Technologic Schools and Universities, and hence will represent an open gate for the new generations to participate in a field of work perceived to be far away from the academic possibilities of developing countries. In addition, the described system will attract young people to the world of Science and the Technology.

In this way, the depicted project constitutes a whole portable training system, attractive and friendly, with capabilities to be adopted as a partner to access the world of science and technology, satellite technology or towards other technological fields such as Electronics, Telecommunications and Informatics.

The system will support research in fields such as three axis stabilization, digital communications, satellite sensors, power systems, payload validation, flight computers, navigation autonomy, and satellite constellations. Those subjects will be addressed shortly with the support of this laboratory tool.

In addition the future work among UNAM and ITSON, related to the use of the PDS in laboratories from Universities, has been mentioned, along with the plans to develop efficient manuals and educative material to encourage the described satellite tool within the university environment.

## References

1. Eyassat, 2007, http://eyassat.com/tiki/tiki-index.php .
2. Israel Tecch, 2007, http://www.technion.ac.il/~pgurfil/projects.html
3. USNaval, 2007, http://www.wa8lmf.net/bruninga/ea467.html .
4. Esaú Vicente-Vivas, Fabián García-Nocetti and Francisco Mendieta-Jiménez, "Automatic maintenance payload on board of a Mexican LEO microsatellite", Acta Astronautica Journal, Elsevier Science,, Volume 58, Issue 3, Pages 149-167, February 2006.
5. E. Vicente-Vivas y D.F. García Nocetti, "Computadora de Vuelo Triplex de Diseño y Manufactura Mexicana para el Microsatélite Satex", Revista Iberoamericana Información Tecnológica, ISSN 0716-8756, Vol. 17, No 1, pp. 69-76, Enero 2006, Chile.
6. E.Vicente Vivas, A.Espinoza M., C. Pineda F., J.R. Tórres F. Y A. Calvillo, "Software de Adquisición de telemetría y control de operaciones para microsatélites", 4° Conferencia Internacional en Control, Instrumentacion virtual y Sistemas Digitales "CICINDI 2002", Pachuca, Hidalgo, México, Agosto del 2002.
7. 7. Y.Tsuda et al, "University of Tokyo's CubeSat "XI" as a Student-Built Educa tional Pico- Satellite –Final Design and Operation Plan", The 23rd International Symposium of Space Technology and Science, Matsue, Japan, 2002.
8. CubeSat Origins, http://directory.eoportal.org/pres_CubeSatConcept.html .
9. The Stanford University CubeSat concept, http://cubesat.info/ .
10. CubeSats Running Projects, http://en.wikipedia.org/wiki/CubeSat#Current_running_projects .
11. H. Heidt et al, "CubeSat: A new Generation of Picosatellite for Education and Industry Low-Cost Space Experimentation ", 14th Annual/USU Conference on Small Satellites, August 2001.