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Project Irazú: Advances of a Store & Forward CubeSat Mission for Environmental Monitoring in Costa Rica.

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Abstract

In 2007, the Government of Costa Rica announced to the world its ambitious goal of turning into the first carbon neutral country by 2021. Following the announcement, governmental institutions, universities, NGOs and private companies have worked arduously on the creation of different initiatives to reach that goal. One innovative project is Irazú, consisting of the design, construction, launch, and operation of the first Central American satellite. The project is not just intended to enable a baseline for training scientists, engineers, and managers in the necessary skills to execute an end-to-end space project. It also aims to demonstrate a CubeSat Store & Forward (CS&F) System that enables transmission of biomass and carbon dioxide fixation data from a remote fast growth tree plantation in the lowlands of Costa Rica to a research facility for its post-processing and analysis. The Irazú project is led jointly by the Central American Association for Aeronautics and Space (ACAE) and the Costa Rica Institute of Technology (TEC). It also involves a variety of national and international stakeholders from government, academia, and industry. This paper is a continuation of previous reports on Irazú that were presented at the Workshop on Small Satellite Programs at the Service of Developing Countries over the last five International Astronautical Congresses. The project has already reached major milestones, such as the approval of the final design presented in the Critical Design Review (CDR), successful assembly of the manufactured structure and the components received from

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different CubeSat component providers, and successful performance during various environmental tests. The mission and satellite system architecture for a CS&F system were defined, which included the three primary components: the remote station, the spacecraft, and the ground segment. Experts from the National Aeronautics and Space Administration (NASA), Kyushu Institute of Technology (Kyutech) and Delft University of Technology (TU Delft) revised the design of Irazú. Advances in the Assembly, Integration & Testing (AI&T) phase are presented and discussed, which include the development of spacecraft components, testing of the communication link, assembly of the satellite and initial results of environmental testing. International cooperation is emphasized in this phase, because Costa Rican engineers carry out testing at the laboratories of the Kyushu Institute of Technology. Furthermore, advances in the satellite frequency coordination process and spacecraft registration for an emerging space nation are presented, as well as the lessons learned from the AI&T phase.
Keywords: CubeSat, Earth observation, offset carbon emissions, remote sensing.

Acronyms/Abbreviations

ACAE	Central American Association of Aeronautics and Space
AI&T	Assembly, Integration & Testing
CDR	Critical Design Review
COMMS	Communications
COPOUS	Committee on the Peaceful Uses of Outer Space
CRC	Cyclic Redundancy Check
CS&F	CubeSat Store & Forward System
CSP	CubeSat Space Protocol
EPS	Electrical Power System
FRR	Flight Readiness Review
IARU	International Radio Amateur Union
ITU	International Telecommunications Union
JAXA	Japan Aerospace Exploration Agency
JEM	Japanese Experimental Module
Kyutech	Kyushu Institute of Technology
LNA	Low Noise Amplifier
MCR	Mission Concept Review
MICITT	Ministry of Science, Technology, and Telecommunications
NASA	National Aeronautics and Space Administration
OBC	Onboard Computer
ORR	Operational Readiness Review
OST	Outer Space Treaty
PDR	Preliminary Design Review
RSSI	Relative Received Signal Strength
SETEC	Space Systems Laboratory
SM	Structural Model
SRR	Systems Requirements Review
SUTEL	Superintendence of Telecommunications
TEC	Costa Rican Institute of Technology
TU Delft	Delft University of Technology

1. Introduction

At the start of the 21st century, the satellite community was experiencing a shift in the way they designed and executed space missions. Advances in the miniaturization of satellite technology, specifically the creation of the CubeSat standard, has allowed engineers and scientists to build and launch spacecraft at a lower cost and with a faster development time than older technologies. This new breed of nanosatellites, with a mass of only a few kilograms, are able to perform the same tasks as satellites in the range of hundreds of kilograms. The reduction in development and launch cost has opened up access to space to new entities, which include universities and emerging space nations, and it has led to the movement called democratization of space.

One of the countries that has decided to enter this new movement is Costa Rica, which is developing Project Irazú. It consists of using ground sensors to monitor carbon fixation in an experimental plot and a 1U CubeSat to transfer the scientific data to a research institution for analysis and publication. The project is a joint effort between the Costa Rica Institute of Technology (TEC) and the Central American Association of Aeronautics and Space (ACAE). Project Irazú is a proof of concept, which plans to demonstrate how nanosatellite technology can be used to transmit data from remote locations to a central location for analysis. The communications protocol that is being developed is called the CubeSat Store and Forward (CS&F) system, which consists of uploading scientific data to the spacecraft, storing it in its internal memory, and transferring it to a ground station upon command. The team decided to monitor carbon fixation for this project to support Costa Rica's goal of becoming a carbon neutral entity by 2021 and to demonstrate an immediate benefit of space technology to a country that had not developed it previously.

Project Irazú has two main objectives: 1) to create capacities related to space technology in an emerging space nation, and 2) to monitor and to collect field data daily to estimate the growth in biomass as a function of environmental variables in a remote, tropical rainforest region [1].

The team has made considerable advances over the last few years (Table 1). The schedule is divided into seven phases, because the team is using a tailored

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version of the National Aeronautics and Space Administration (NASA) project lifecycle. There are reviews for each of the first five phases of the project (Table 1). This is to ensure that the team is following the correct procedures and executing the project in a responsible fashion. Only after an external group of experts has approved the work is the team allowed to advance to the next phase. The experts carrying out this work on Project Irazú are from different international institutions including the NASA, Kyushu Institute of Technology (Kyutech), Delft University of Technology (TU Delft), and Ad Astra Rocket Company. Project Irazú is currently in Phase D, working on the assembly, integration, and testing (AI&T) of the systems, which will be the focus of this paper.

Table 1. Phases of Project Irazú and deliverables.

Phase	Time Period	Deliverable
Pre-Phase A: Mission Definition	Jan 2015- July 2015	Mission Concept Review (MCR)
Phase A: Requirements Definition	Aug 2015- Nov 2015	System Requirements Review (SRR)
Phase B: Preliminary Design	Nov 2015- Feb 2016	Preliminary Design Review (PDR)
Phase C: Final Design	March 2016- July 2016	Critical Design Review (CDR), CubeSat subsystems, ground station components, ground sensors
Phase D: Assembly, Integration and Testing	Aug 2016- March 2018	Flight Readiness Review (FRR), CubeSat flight model, mission control, ground segment, Operational Readiness Review (ORR).
Phase E: Mission Operations	April 2018- Sept 2018	CubeSat is operating in orbit and communicating with remote/ground stations.
Phase F: Mission Disposal	Oct 2018	Final mission report, lessons learned, scientific report.

2. CubeSat Store and Forward System

The Store and Forward protocol is a technique used in telecommunications that consists of sending data to a node, storing it and transmitting it to another node after a given period [2]. It was created in the 1970´s to manage networks that had low bandwidth connections and basic transmitters (these had very low memory, which led to frequent saturation). The Store and Forward protocol was useful for these networks, because the transmitter stored the incoming data and waited until there were other “free” transmitters to forward the information and avoid saturation.

When the networks became more sophisticated, the technique became obsolete until the early 1990’s, with the growth in popularity of small satellites, that were in the range of 100 – 500 kg. The design of Irazú shows that a 1 kg satellite can fulfill the same function as the satellites of the 90’s, thanks to advances in microelectronics. This concept will be tested for the first time using a 1U CubeSat in 2018, with the operation of the Irazú satellite [3].

A CS&F system consists of at least three components: the remote station, the satellite, and the communication station (Figure 1). The remote station is an autonomous communication station that collects scientific data from sensors that are located in an area with difficult access and limited signal. Once the satellite is in the line of sight of this station, the data is transmitted and stored in its internal memory. The communication station then sends a signal to collect the scientific data and pre-analyze it. The simplest CS&F consists of a unit of each component but it could be developed with more remote stations, satellites and communication stations, which would result in a transmission system of real-time scientific data around the world using cost efficient spacecraft and ground stations.

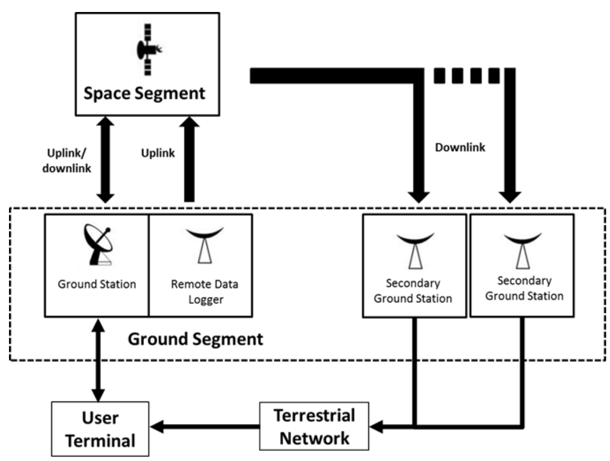

Fig. 1. Architecture of the CubeSat Store and Forward System.

3. Science

3.1 Scientific Mission.

The scientific mission is framed to respond to one of the most significant global threats: global climate change. Irazú will focus on how tree plantations fix atmospheric carbon on a daily basis and how the rate of carbon fixation is affected by changes in environmental variables. This contribution is relevant because, to the best of our knowledge, there have been no studies that

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have provided daily data to understand how planted trees grow and accumulate biomass. Daily measurements of tree diameters (growth) are unprecedented in forest ecology and climate change research, given that previous studies used only annual averages. The general objective of the science mission can be formulated as:

To monitor the carbon sequestration, which is an environmental service, of a forest plantation and to study the dynamics of biomass growth and its relationship with environmental variables on a daily *basis.*

To accomplish this objective, the scientific mission team is developing new technologies to improve efficiency, precision, frequency, and automation of data collection to measure tree growth. Hence, the innovation of Project Irazú is to migrate from manual measurements of tree diameter to multiple, fully automated digital measurements, which are taken virtually in real time and transmitted using a satellite link, a cellular network, or a radio frequency network.

3.2 Pilot Experimental Study

To understand how tree diameter growth varies and how precise the daily measurements need to be, a pilot study was established in March 2016 in a commercial *Gmelina arborea* (fast growing tree) forest plantation [3], which was 1.5 years old and located in the northern lowlands of Costa Rica. At this site, we also installed an automatic weather station and three plots with 40 trees per plot (Fig. 2). The diameter and height of all trees were measured manually every month.

After 10 months of measurements, the general results were: a) average monthly rainfall 280 mm, average temperature 26.6 C°, average relative humidity 93%, b) average growth rate of tree diameters, 3mm/day, equal to 11cm/year, and c) estimated annual accumulation of total biomass (areal + root) 39 Mg/Ha, total carbon 18 Mg/Ha, and equivalent CO2 79 Mg/Ha. All calculations were made using models that were recommended in the literature [4], [5], [6], [7], and [8]. These results demonstrated a remarkably high rate of diameter growth and equivalent fixation of CO_2.

3.3 Experimental Design and Data Collection

Once the pilot study concluded, we established the final experimental design in January 2017 on a property owned by TEC, located in the province of Alajuela, County San Carlos, in the North of Costa Rica. This experimental site was selected because of its secure perimeter and access to electrical power. The region's topography is relatively flat, with an average slope of 1.24° (±1.51°), an elevation of 35 m -110 m, mean annual temperature of 24-27°C, and an annual rainfall of 1950-3000 mm. The climate in the region has a highly variable dry season for 0-3 months [9]. Three plots of 180 m^2 (12 m x 15 m) each were established at the selected site. This site will provide all the experimental data to be transmitted to the satellite during 2018. Therefore, these trees will be 1 - 1.5 years of age, and the estimated daily diameter growth rate will be of 0.3 mm (see section 3.2).

The monitoring of daily growth (diameter) will be carried out by placing electronic dendrometers (under final calibration) on five selected trees. The five electronic dendrometers will be synchronized with a data aggregator that stores the information. The daily average of tree diameter growth will be transmitted to the satellite.

In the middle of the site, a tower 15 m high was placed and it contains: a) an automatic weather station, b) two pyranometers that measure the incoming and outgoing solar radiation, and c) two photosynthetic active radiation sensors that measure radiation between 400 -700 nm. The information from all sensors in the tower, which include the dendrometers and soil moisture sensors, will be transmitted to a data aggregator every 30 min. Also, the tower will be used to install the antenna for the satellite data transmission system, solar panels, and data aggregators.

Fig. 2. Pilot experimental site for Project Irazú in Los Chiles de Alajuela, Costa Rica. Areal overview of plots and tree plantation.

3.4 Integration of Ground Instrument

To measure daily diameter growth and environmental factors the team is designing a basic data-logger (named Eco-logger) that will control two main tasks: a) collection of all data from remote sensors (i.e., dendrometers, weather station, and soil moisture station) and b) packing of all collected information in a single data packet that is ready to be transmitted to the satellite relay.

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The Ecologger is a microcontroller-based device, which holds a repetitive software pattern to measure environmental variables and poll data from remote sensors at a configurable frequency. Additionally, the Ecologger contains a precise time reference, which enables tracking measurements at the time (and therefore, events) when they occurred. It also offers an external storage system using an SD card that acts as data backup storage to retrieve information if communication with the satellite is lost and to verify the correct transmission of the experimental station. Additionally, it has a backup communication interface using a USB protocol, which can be used to connect to a different transmitter or to connect to ground-based communication technologies if required. On the communication interface, the Ecologger acts as a data aggregator, featuring an XBee master node, which can collect information from all the remote dendrometers (Fig. 3).

Similar to the dendrometer design (battery operated), the Ecologger will use a battery to support its life operation (including an energy-saving mode). For the initial prototype and test runs, one of the plantation's electrical outlets will be used. Future implementations will use a lithium battery that is dimensioned to support up to 10 days of continuous operation and connection to a solar panel.

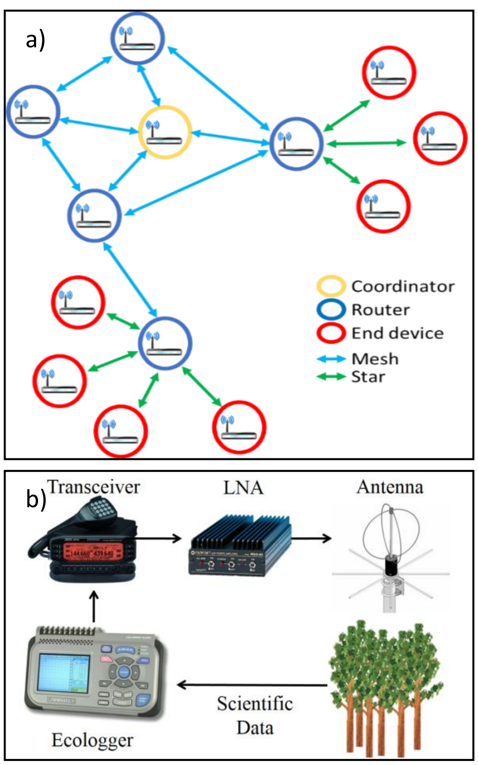

Fig. 3. a) Wireless transmission network and b) Block diagram of the remote ground station for Project Irazú.

3.5 Remote Communication Station

The objective of this station is to create an autonomous communication system that will collect the data from the ground sensors and transmit it to the spacecraft. The first element to consider is the Ecologger, which packages the data and sends it to the transceiver. This device creates a signal that passes through the low noise amplifier (LNA) and finally to the antenna for transmission to the spacecraft. An omnidirectional antenna was selected for this communication station, because a directional antenna must include rotor control. This feature is difficult to implement in an independent station given that the orbital elements of the spacecraft must be updated frequently during operations. The remote communications station design demonstrates a cost-efficient and simple, yet robust mechanism, for environmental monitoring.

4. Assembly, Integration, and Testing

The AI&T phase consists of building or procuring the different subsystems that were defined in the previous phase (Phase C: Final Design) and integrating them to create the final product, a 1U CubeSat system. This section will present the different subsystems that have been developed, along with a summary of the assembly and testing procedures that will be carried out at the end of this phase. Furthermore, an overview of the assembly and integration of the ground station is presented.

4.1 CubeSat Subsystems

The CubeSat is divided into four subsystems: the structure, electrical power system (EPS), communications (COMMS), and onboard computer (OBC). The following subsections present an overview of the activities that are related to each subsystem during Phase D of the project. Details about the design of each subsystem is found in [10].

4.1.1 Structure

The 1U CubeSat structure was designed by engineers at TEC and built by the precision manufacturing unit of the National Learning Institute (INA), a Costa Rican autonomous institution that specializes in technical education. This is one of the most critical components of the project, because it is a demonstration of the capabilities that are available in Costa Rica, that are not necessarily exploited with a space-focus.

The structure was designed considering the requirements that were specified for a 1U CubeSat in the Japanese Experimental Module (JEM) Payload Accommodation Handbook [11] published by the Japan Aerospace Exploration Agency (JAXA). It consists of four rails (one on each side of the cube), that allows the CubeSat to be inserted into a standard CubeSat launch

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mechanism. Two deployment switches are incorporated into opposite rails. This triggers a signal to the EPS once the satellite has been deployed into space. The other two rails include spring plungers that aid with the separation of the spacecraft once it is deployed. The material used for the structure was Aluminum Alloy 6061, which resulted in a final mass of 120 g.

Two models of this structure were manufactured: a structural model (SM) and a flight model. The SM was sent to Kyutech (Japan) for initial testing and verification of the requirements, and the flight model is in Costa Rica for assembly and integration (Fig. 4).

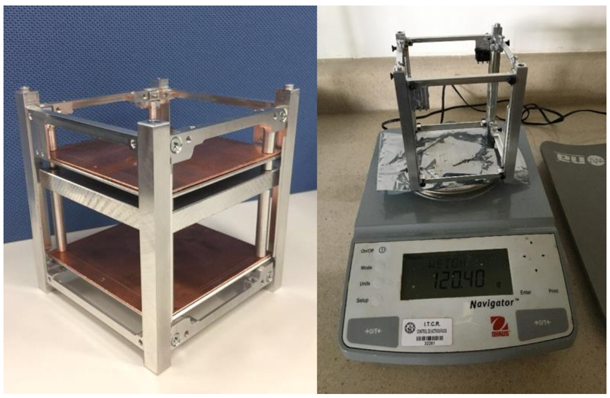

Fig. 4. Structural model of the 1U Irazú structure prepared for vibrational testing (left). Flight model of the structure being tested for mass requirements (right).

4.1.2 Electrical Power Systems

To provide the power needed for the CubeSat mission, the EPS consists of five solar panels and a battery system. These are designs that have already been tested in space by the provider to reduce the risks. The provider selected was GomSpace, with its "NanoPower P31u" as a power source, in combination with the "NanoPower P110" solar cells. The source of energy consists of two power buses with voltages of 3.3 V and 5 V, which are compatible with the requirements of all the other subsystems.

As an essential component of the CDR, it was proven that enough power would be generated with only five solar cells [10], even under worst-case scenario lighting conditions. The EPS system was tested and verified up to August 2017, and after verifying its working specifications compared to the CDR calculations, it is ready for integration in September 2017.

4.1.3 Communications

The CubeSat communications system consists primarily of a half-duplex, software configurable transceiver: the NanoCom AX100. It is responsible for sending the telemetry and receiving the commands for the uplink/downlink of the scientific data.

The telemetry data are obtained from the following subsystems: EPS for battery charge, the OBC for timestamp and gyroscope, and COMMS for the relative received signal strength (RSSI). In the main operation mode of the CubeSat, the scientific data for downlink will be obtained from the OBC and, for the uplink, data will be obtained from the Remote Ground Station, so the CS&F can be performed. Operators in the ground segment (mission control) can access the other operating modes.

The antenna coupled to the transceiver operates in the ultrahigh frequency (UHF), and it is circular polarized with an omnidirectional radiation pattern. The highest gain is 1.4 dBi (along the Z-axis of the CubeSat). The lowest gains are 0.6 to -0.3 dBi (along the X- and Y-axes) (Fig. 5).

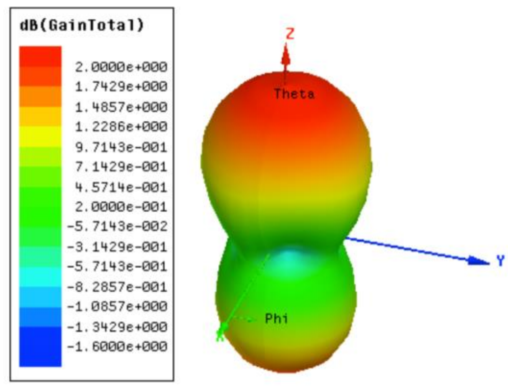

Fig. 5. Radiation pattern of UHF antenna: NanoCom Ant430 [GomSpace, 2017].

FLAG		c0
AX.25 Header	INIT	0
	Source Callsign	82
		b0
		62
		60
		60
		a4
		60
	Callsign Destination	82
		b0
		62
		60
		60
		a4
		61
	Control Field	3
	PID	f0
AX.25 Data Field	CSP Header	94
		70
		6c
		0
	CSP Packet	0
	CRC-32	51
		fe
		67
		49
FLAG		c0

Fig. 6. AX.25 data frame, in KISS mode, for the requested file upload command.

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All scientific data sent to the ground stations is encoded into an AX.25 protocol by the transceiver. This data frame includes the AX.25 header, the data field, and a 16-bit cyclic redundancy check (CRC) for error detection. The software in the AX.25 header configures a call sign with SSID, for destination and source. In the AX.25 Data Field, an encoded header is added for the CubeSat Space Protocol (CSP), which contains the destination/ source node, ports, and priority, so the packets can be routed correctly in the communications architecture (Fig. 6).

In the developing process, a FTDI cable (USB-Serial Converter) was modified to have an external power supply, because the AX100 undergoes an external reset when it does not get enough current. The voltage of the power supply is set to 3.3V with a current limitation of 1A. This way, the transmission was achieved with the minimum power established in the "tx_pwr" parameter of the AX100, consuming approximately 0.3 A. The "tx_pwr" parameter goes from one to three. Initial tests demonstrated that it was possible to realize the transmission to maximum power with the EPS (NanoPower P31u).

4.1.4 Onboard Computer

The OBC is one of the core subsystems of the Irazú Satellite. It is in charge of receiving commands from both the ground station and the remote transmitter. Then, the computer decodes and executes these commands, together with other satellite subsystems like EPS and Communication. The OBC for the Irazú project is based on the GomSpace NanoMind A3200. This computer features a high performance microcontroller that is based on the AVR32 MCU architecture. It has 512 KB of built-in Flash memory, 32KB of FRAM for parameter configuration, Real Time clock and calendar capabilities, and on-board temperature sensors. For communication with other subsystems, the Irazú OBC makes use of the CSP over an I2C bus. The onboard computer was selected according to the requirements from the PDR/SRR. It also included the mapping of structural and functional requirements into a physical architecture (Fig. 7). The onboard software is split into a service layer (bootloader+operating system+libraries) and an application layer. The service layer handles all interfaces between software and hardware components. It also includes data interfaces to communicate with the radio transceiver and the electrical power unit.

The onboard software is implemented as a multi-task application intended to address the requirements specified above for each of the mission phases. Once the satellite passes the early operation period, the beginning of operations is done by changing the operational mode to the main mode, where the satellite will start to collect and relay data to the ground systems.

In this design, the use a synchronized main loop for all operations is proposed. The main advantage of this approach is that everything is dependent on one timer and all tasks will run synchronously, while the interrupts and priority handling is managed separately. The main loop starts with initiating the synchronization timer, which controls the end of this loop and the start of the next loop. Every synchronization period a command is sent to the slave subsystems, so they know that the OBC is alive and they should perform its core measurements at this command.

The watchdog timer will be preset every synchronization cycle. In case the OBC fails, the watchdog is not cleared from reaching the zero count, and the OBC will reset automatically. The functions for completing the proper satellite operation are meant to be implemented using the software development tools provided by the manufacturer. These functions include all the stated according to the requirements in the previous sections.

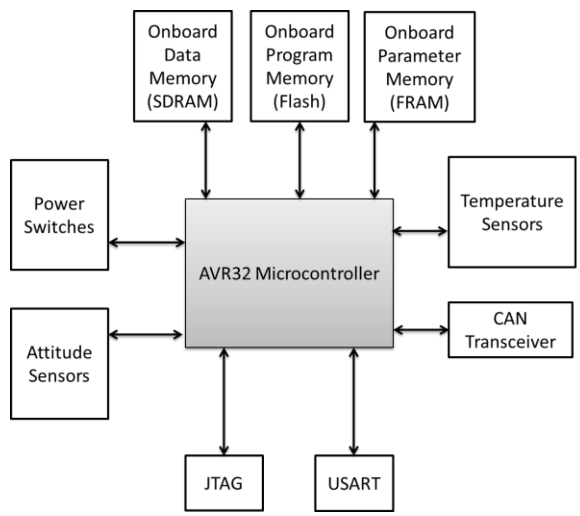

Fig. 7. Project Irazú onboard computer architecture

4.2 Assembly

The assembly of the CubeSat will take place in October 2017 in a clean room class 100,000 that is owned by MOOG Medical, a medical manufacturing company that is located in the Coyol Free Zone, one of the project's sponsors. The assembly procedure is based on the CubeSat Integration Manual that was written by researchers at the California Polytechnic State University [12]. Currently, assembly manuals for the CubeSat are being developed at the TEC's Space Systems Laboratory (SETEC Lab). Activities that are related to the assembly include verifying the internal component distribution of the final designs, verification of final mass distribution, and an overall compliance to the requirements set by JAXA, the launch provider, and the CubeSat standard. The Irazú team has taken the necessary precautions when handling the spacecraft

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components, which include the use of safety gloves, an anti-static mat and grounding each of the engineers, who test the subsystems, to avoid electrostatic discharges. Fig. 8 displays the advances of the integration of the CubeSat components in the 1U structure.

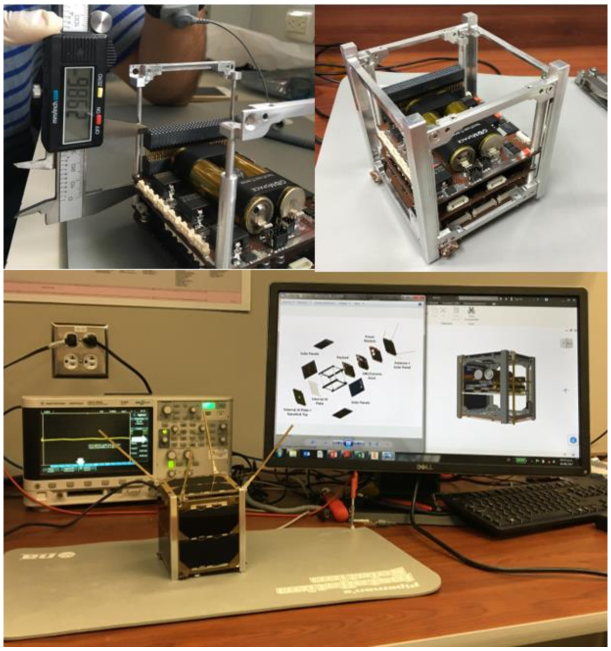

Fig. 8. Measurement of internal component separation of the spacecraft, integration of internal CubeSat components, and full CubeSat integration for Project Irazú.

4.3 Testing

The environmental tests to be performed on the Flight Model are the Vibration Test and the Thermal Vacuum Cycle test. The purpose of the Vibration Test is to demonstrate that the satellite can withstand the test levels of sinusoidal vibration, random vibration and quasi-static load (sine-burst) without structural failure, no malfunction of components (accidental turn-on or deployment) and no damage to electronic, mechanical or electromechanical components. The Thermal Vacuum Cycle Test demonstrates that the satellite was manufactured properly, that it can survive and properly operate in space and that it can withstand the thermal stress induced by temperature cycles. The two models of the satellite are tested under different test levels:

- Qualification Test level (QT) is set as the maximum predicted environment plus a margin. A dedicated model, which is called the SM, will be used for this test. The main objective is to detect design defects.
- Acceptance Test level (AT) is equal to the maximum predicted environment, and the FM model shall be used for this test. This test is aimed to detect workmanship and material defects.

The environmental tests are carried out at the Center for Nanosatellite Testing (CeNT) of the Kyushu Institute of Technology, under the specifications of the JEM Payload Accommodation Handbook-Vol.8, and Structure Verification and Fracture Control Plan for JAXA Selected Small Satellite Released from J-SSOD [11].

4.3.1 SM Vibration Test

During the first week of July 2017, the SM of Irazú was tested at Kyutech. The SM was prepared by adding some aluminum, PCB, and brass plates to match the weight and center of mass of the actual components (Fig. 9).

A structural analysis using a finite element method simulation was made to evaluate the response of the modeled structure to the expected load, to determine the natural frequencies and set the test frequency range accordingly. From that preliminary simulation, we determined that Irazú satisfied the structural requirements for satellites released by Japan’s Small Satellites Orbital Deployer (J-SSOD)

Before the actual test, a detailed test plan and a step-by-step SM assembly document were prepared. To perform the test, the Irazú SM was inserted into a Poly-Picosatellite Orbital Deployer (P-POD) with two dummy satellites. The structure was then attached to the vibration machine and monitored by accelerometers.

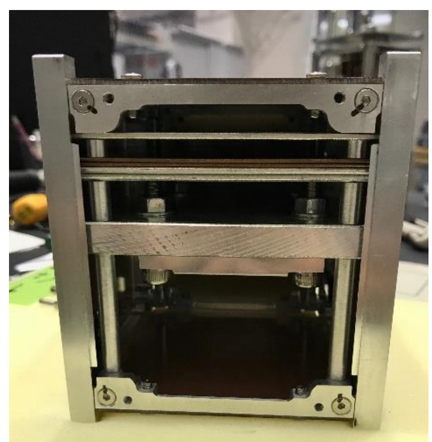

Fig. 9. Structural Model of the Irazú satellite.

The test is performed in all three axes, which consider several vibration input profiles as follows:

- Signature Check: The test consists of a frequency sweep from 5 Hz to 2000 Hz during 60 s to determine the natural frequencies of the satellite. It will be applied before and after every test profile to detect any displacement on the resonant frequency.

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- Random Vibrations: The test consists of random vibrations within a Power Spectral Density (PSD) profile for a range of frequencies from 20 to 2000 Hz. For Irazú, a combination of every possible launch vehicle was used (SpaceX Dragon, ESA ATV, Orbital Cygnus and JAXA HTV). A combined maximum envelope profile was calculated (Fig. 10). Over the maximum expected value, an additional margin of +3 dB/dec was added to the PSD. Under those conditions, the overall input was 6.8 grams. The test duration was set to 120 s.

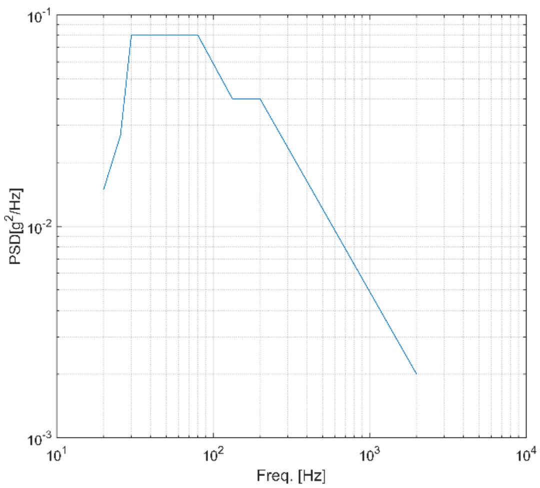

Fig. 10. Envelope of the random vibration profiles.

- Sine Burst test: The test used sinusoidal base waves to apply a quasi-static load into the satellite body at a specific frequency. The highest acceleration load of all possible launch vehicles was selected for the analysis (Orbital Cygnus: 18.1g). The applied load was 18.1g x 1.25 = 22.6 g, at a frequency of 30 Hz with, at least, 20 waves of the maximum load applied to the body. The sequence of the test for each axis is: 1) Signature Check. 2) Random vibration. 3) Signature Check. 4) Sine Burst. 5) Signature Check.

As an example of the results, we provide the X-axis PSD profile of the before and after vibration test Signature Checks (Fig. 11) and the sine burst profile applied to the SM (Fig. 12).

4.3.1 Flight Model Vibration Test and Thermal Vacuum Cycle Test

The environmental testing for the FM is scheduled for November and December of 2017 in Kyutech, Japan. The flight model will be subjected to a Thermal Vacuum Cycle test and a Vibration test. For the thermal vacuum test, a vacuum chamber with a special cooling jacket is used to surround the satellite with liquid nitrogen (LN2) at a temperature of -192°C. Thermal resistances are placed around the satellite to control the temperature and generate thermal cycles as if the satellite was orbiting the Earth. During the thermal cycles, the Irazú satellite will be powered using its battery, which will be recharged by an external energy source. There will be access ports to the chamber, which will allow monitoring the temperature of various critical components of the satellite during the test.

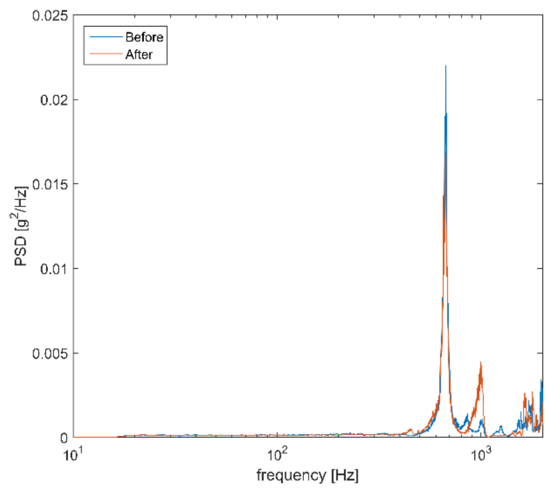

Fig. 11. Signature check of the SM.

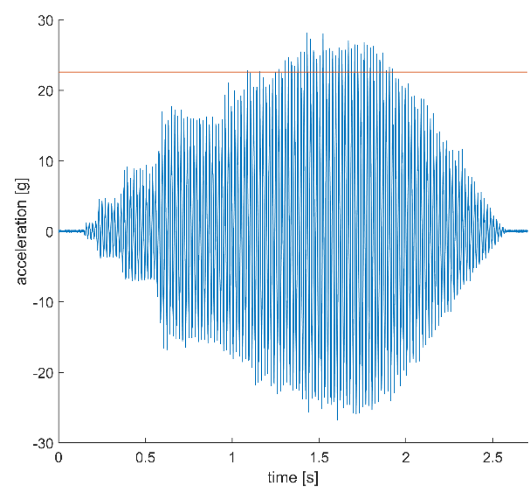

Fig. 12. Sine burst applied to the SM

RF transmission, the OBC receiver, and antenna deployment will also be tested during the Thermal Vacuum Cycle test. The Vibration test for the flight model will be performed following the same procedure for the SM, but it will be done at the AT level, which means that maximum expected environmental conditions will be employed without any margin. After every environmental test, a functional test is required to verify the proper operation of the satellite.

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4.4 Ground Stations

Except for the customized software modem, all ground station hardware is commercial off-the-shelf (COTS) amateur radio hardware. This hardware was selected to meet the requirements that were imposed by the uplink and downlink budgets.

The Remote Ground Station is formed by a Kenwood TM-D710G Radio (46.9 dBm), a Microset UHF power amplifier RU 2-45 (46.5 dBm) and an omnidirectional circular polarized UHF antenna (5.5 dBi). The computer that runs the CSP application is a Raspberry Pi 3 model b+, running in Raspbian (Debian) (Fig. 13).

Fig. 13. M2 Inc. EB-432 antenna and Kenwood TM-D710G used to run the ground station for Project Irazú.

Scientific data is collected from sensors wirelessly, using the radio frequency module: RFM69HCW (Fig. 14). After all data is obtained from the network of sensors and stored in the Raspberry, each data frame is encoded with the same AX.25 data frame used with the AX100 transceiver.

Both uplink and downlink are performed at a baud rate of 9600 bps. 1200 bps was originally intended to be used, but after testing between both radios, better performance was identified at 9600bps. This change was made with the intention of reducing risks in transmitting the scientific data by using a higher baud rate.

The CSP protocol implements interfaces and drivers, to transmit data over different protocols to conserve the CSP structure. A KISS interface is already carried out in the CSP GitHub, for serial communication.

The approach of the KISS interface is to send data to the CubeSat radio and/or OBC over a USB-Serial converter. In case the AX100 is in AX.25 mode, the AX.25 header is added by its microcontroller. Therefore, the AX.25 header is not included in either the KISS CSP interface or the Kenwood in KISS mode. To include the AX.25 Header and the correct CRC, a "KENWOOD" interface was developed inside the CSP protocol that was based on the KISS interface.

The main problem faced with the link was the modulation incompatibility between radios. The AX100 uses G3RUH FSK modulation and the TM-D710G uses FM modulation with two-tone AFSK encoding that is generated by its built-in TNC.

Taking advantage of the "DATA" 6-pin mini-DIN connector in the TM-D710G, which includes an audio data IN/OUT pin and a PTT pin, a software TNC modem was implemented. In this way, the G3RUH FSK modulation can send and receive audios that contain the encoded data. In fact, plenty of software modems for amateur radios exist. The open source software called Direwolf was selected for this operation. With just a .configuration file, the encoding from a virtual serial port to the audio output of the Raspberry Pi can be done easily. The PTT can be controlled with a GPIO pin, and it is configurable with Direwolf.

Fig. 14. Raspberry Pi 3 and RFM69HCWmodule used to collect scientific data.

5. Lessons Learned

Irazú is the first satellite project developed in Costa Rica, and many lessons have been learned during its development. This section presents the most relevant lessons that we experienced during Phase D of the project.

5.1 Frequency Registration

The registration of the operating frequency of the satellite is necessary to launch the spacecraft into space. This is a long process, which takes a minimum of nine months. It consists of applying for an operating frequency with the International Telecommunications Union (ITU) and in parallel with the International Amateur Radio Union (IARU), because CubeSats operates in amateur radio frequency bands. The former process consists of using ITU´s SpaceCap, which is software utilized to prepare the application. With this tool, the operating frequency and technical

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specifications of both the spacecraft and the ground systems are specified. For Irazú, the application was prepared with the help of the Ministry of Science, Technology and Telecommunications (MICITT), because the applications must be submitted by a governmental agency.

The application procedure with IARU is usually performed in parallel to avoid delays in the frequency registration process. It consists of specifying technical details of the communications equipment (similar to the ITU application) and a spacecraft operator, which must have an amateur radio license. Another option to this procedure is to obtain a scientific license from the government to operate the satellite, which is the course taken by the Irazú team. By working closely with MICITT and the Superintendent of Telecommunications (SUTEL), a license is currently being procured that will allow TEC to operate the satellite for the defined period that it will be in orbit. The team expects to have the operating frequency registered by December 2017.

5.2 Spacecraft Registration

Project Irazú represents Costa Rica and Central America's first experience in space use and exploration. Through the experience gained in this project, ACAE and TEC aim to develop in the region the human talent and capabilities to completely carry a space mission from conceptualization to design and execution. The capabilities needed to successfully carry on future missions include developing the legal and political mechanisms that constitute the international regulatory framework for space activities, in accordance with the Outer Space Treaty (OST).

As any other regulatory scheme, international space law establishes alongside obligations, a set of rights or freedoms derived from its core objectives. First, outer space is unrestricted for exploration and use by all nations for peaceful purposes. Secondly, its use should benefit all people. Third, it should be an instrument for international cooperation. In this sense, the right of Central America represented by Costa Rica to access and use outer space is granted by all international treaties that constitute international space law.

The five main space treaties conceived by the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) are listed as follows [13]:

- Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty or OST)
- Agreement on the Rescue of Astronauts the Return of Astronauts and the Return of Objects Launched into Outer Space (Rescue Agreement)
- Convention on International Liability for Damage Caused by Space Objects (Liability Convention)
- Convention on the Registration of Objects Launched into Outer Space (Registration Convention)
- Agreement Governing the Activities of States on the Moon and Other Celestial Bodies (Moon Agreement)

Among the international treaties relating to activities in outer space, Costa Rica has only adopted in its national jurisdiction the Registration Convention, approved by the Law 8832 of the Legislative Assembly of the Republic of Costa Rica on May 10, 2010 [14]. The registration process of the CubeSat is being conducted with the Ministry of Foreign Affairs of Costa Rica.

Space treaties establish a series of obligations for states looking to become space faring nations [15]. These ensure that all activities carried out in space have peaceful purposes, and that states remain liable for the activities of their citizens in space.

International registration of objects is an obligation placed upon states by the United Nations General Assembly. Each state must provide information regarding the function of the object, launching state or states, designation of the space object, information on the launch including territory and date, and orbital parameters such as nodal period, inclination, apogee and perigee.

5.3 Subsystem Manufacturer and JAXA Requirements

Safety reviews of any launch provider are processes in which many proof documents are requested. Some of the critical safety features that shall be examined by JAXA and are related to spacecraft subsystems are:

- Energizing inhibits (RBF pins and deployment switches).
- Battery protection circuits (overcharge, over discharge, overcurrent and external short circuit).
- Antenna deployment system.
- Electrochemical cell screening and matching for battery construction.
- Battery assembling and testing.

Most of these documents are considered as classified by spacecraft subsystem manufacturers and this implies that a negotiation should be carried out to ensure safety compliance. This can be solved by setting a non-disclosure agreement between some or all the involved parties. In the case of Irazú, this was the solution to this problem. We do strongly recommend negotiating these terms from the beginning with the subsystems' manufacturer to avoid unnecessarily affecting the schedule. Naturally, the manufacturer will like to

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protect its intellectual property, while the launch provider would like to know every detail possible about the components they are flying. It is important to understand the implications of the lack of access to information that the developing team will have.

5.4 Scientific Component

Our experience points out that in the planning and development of a CubeSat project, a scientific mission that is properly embedded within the context of society's needs and aspirations should be included, and that it must represent an outstanding challenge to the technical and scientific team. This will trigger innovation by generating new solutions to major problems. In our case, the selected scientific mission has garnered social attention. This has given the mission significant national and international projection, and a foundation to achieve financial, institutional and political support, all in an attempt to solve a relevant problem in an interdisciplinary fashion.

5.5 Risk Reduction

A mission in a developing country should be posed as a careful balance between risk minimization and technical challenges. The use of an international evaluating group subjecting the development to the NASA Systems Engineering Model has been fundamental in ensuring that the mission remains innovative and within the technical capabilities of the country, while bounding the risk levels. Evaluation of the PDR and CDR by the external team was a key source of feedback during the intermediate steps of the mission.

6. Conclusions

Project Irazú has reached various milestones in the last year, which include technical and scientific advances in the AI&T phase, which will lead to the launch of the CubeSat in March 2018. This innovative mission will contribute to the way we measure growth of tree diameters, and it will provide the foundation for future development of research in forest ecology, agriculture, and natural forest conservation and restoration to offset carbon emissions. This mission will also contribute to the country's goal of becoming carbon neutral in the near future.

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