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Irazú: CubeSat Mission Architecture and Development

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Abstract

The Central American Association of Aeronautics and Space (ACAE) and the Costa Rican Institute of Technology (TEC), in partnership with industry and government, have identified the promotion of aerospace as a very promising strategy for economic, scientific, and technological development in Costa Rica. Several studies, including a state-of-the-art mapping of aerospace industry made by ACAE, the Central American Institute of Business Administration (INCAE) and the Costa Rican Foreign Trade Agency (PROCOMER) [1], have identified actions to enable the development of the aerospace sector in the country. Among them, a significant catalyst would be a practical demonstration of the technical capabilities to develop a space engineering project. The Irazú project is an innovative mission taking place in Costa Rica, which aims to launch the first Central American satellite in orbit by 2018. The project, led by ACAE and TEC, has two main objectives: a) to complete a space project life-cycle, and b) to develop a platform to monitor the growth in biomass of planted trees to offset carbon emissions and to help reduce Global Warming. This project supports the efforts of Costa Rica to become the first carbon neutral country in the world. The mission is divided into three segments: the remote station, the space segment, and the ground segment. The remote station is located at the northern region of the country. Sensors will be placed there to measure tree growth, soil humidity, and other weather variables. Collected data in the remote station will be transmitted to the space segment, a 1 unit (1U) CubeSat in Lower Earth Orbit (LEO), that in turn will transmit the data to the ground segment. The latter includes the ground station, mission control, and a data visualization center, which will process the scientific data to make it available to the public. To validate the execution of the project and to strengthen international cooperation, international partners from Japan, the Netherlands and the United Kingdom have been enlisted to train Costa Rican engineers, evaluate the work planning process, provide testing facilities, and provide launching services. The Irazú mission follows the NASA project life-cycle as a reference, and it is divided into seven phases. This paper focuses on the results of Phase C, which consists of the definition of the critical design of the mission. Moreover, the lessons learned will be described, focusing on the issues relevant to developing countries that aim to develop similar projects.
Keywords: CubeSat, Earth observation, fundraising, offset carbon emissions.

Acronyms/Abbreviations

ACAE	Central American Association of Aeronautics and Space
ACS	Attitude control system
CAN	Controlled Area Network
CDR	Critical Design Review
CEO	Chief Executive Officer
DBH	Diameter at breast height
EPS	Electric power subsystem
I^2C	Inter-Integrated Circuit
IMU	Inertial measurement unit
ISS	International Space Station
ITAR	International Traffic in Arms Regulation
JAXA	Japanese Aerospace Exploration Agency
Kyutech	Kyushu Institute of Technology
LEO	Low earth orbit
LaSEINE	Laboratory of Spacecraft Environment Interaction Engineering
MCR	Mission Concept Review
MCU	Microcontroller Unit
MS	Mechatronics Section
NASA	National Aeronautics and Space Administration
OBC	Onboard computer
PDR	Preliminary Design Review
RCCR	Radio Club of Costa Rica
SFE	School of Forest Engineering
SRR	System Requirements Review
TEC	Costa Rican Institute of Technology
TRL	Technology readiness level
TNC	Terminal node controller
UHF	Ultra-high frequency
USD	United States Dollar

1. Introduction

The Central American Association of Aeronautics and Space (ACAE) and the Costa Rican Institute of Technology (TEC) are collaborating to develop an innovative project in the Central American region called Irazú. Irazú is a proof of concept for the development of a complete life-cycle space mission using CubeSat technology and a standard satellite communications platform to collect daily data from remote ground locations and provide monitoring, reporting and verification capability to on-going research on the topic.

TEC conducts a series of research programs related to the ecology of tropical forests. The main challenge that scientists face in tropical regions is the difficulty of having to retrieve the data on a daily basis from remote locations where telecommunications coverage is very limited [2]. With Irazú, a solution will be presented to satisfy this need, which could be applied to a larger scale for future missions.

1.1 Objectives

The Irazú project has two main objectives:

1. To demonstrate the capability to develop and operate an aerospace engineering project in Costa Rica.
2. To develop a scientific mission that will allow Costa Rican scientists to collect field data daily to estimate the growth in biomass as a function of environmental variables in a remote tropical rainforest region.

The first objective relates to all the components necessary to execute a space-related project, including developing a well-trained technical team, identifying key organizations interested in space mission developments and operating the system once the spacecraft is in orbit. It is expected that the process will develop a cadre of highly trained professionals enabling them to execute future space missions to address other Costa Rican needs. The second objective describes the purpose of the scientific component of the mission. It seeks to address one of the country's needs, more specifically the study the ecology of its rainforests and forest plantations.

1.2 Stakeholders

The stakeholders of the Irazú mission and their responsibilities are presented in Table 1. The relevant stakeholders in this project are ACAE, TEC-MS, TEC-SFE, Kyutech, the Radio Club of Costa Rica and the project sponsors.

Table 1. Stakeholders of the Irazú project.

	Description	Responsibilities
ACAE	ACAE is a non-governmental organization with the main purpose of promoting projects of innovation and development in the aerospace field.	ACAE created the project in 2010. Its main responsibilities include creating strategic alliances and fundraising for the purchase of the CubeSat components.
TEC-MS	The TEC Mechatronics Section (MS) is part of the School of Electronic Engineering. It was created in 2010 to meet growing demands for mechatronic engineers in Costa Rica.	TEC-MS is responsible for the technical component of the project, which includes the CubeSat, ground stations and systems engineering. It will also handle mission design and operations.

TEC-SFE	The School of Forest engineering (SFE) of TEC was created to perform scientific research on Costa Rican forests.	TEC-SFE is responsible for the scientific component of the mission, including sensor development and placement.
Kyutech	The Kyushu Institute of Technology (Kyutech) is a Japanese university with an aerospace laboratory that has extensive experience in small satellite missions.	Kyutech will provide the facilities for testing of the spacecraft. Additionally, they will be responsible for securing the launch opportunity.
Radio Club of Costa Rica	The Radio Club of Costa Rica (RCCR) is a non-profit organization for amateur radio operators.	RCCR advises on the technical aspects of the ground stations (design, construction and testing).
Project sponsors	The sponsors include EY, Toyota Motor Corporation, Comunicación Corporativa, Coyol Free Zone and the civil society of Costa Rica.	The sponsors will be the funding agent of Irazú.

1.3 Project requirements and constraints

From the project objectives, four requirements were derived.

1) The project shall enable the training of Costa Rican engineers in completing a full life-cycle space engineering mission according to well-recognized international standards.
2) The project shall enhance the capabilities needed by the country to become a carbon-neutral entity.
3) The project shall enable the capabilities to develop space engineering projects in Costa Rican institutions.
4) The project shall make use of the CubeSat standard for the design of the flight segment of the mission.

Additionally, three main projects constraints were identified. These are:

1) The project shall not use any component that is restricted by ITAR (International Traffic in Arms Regulation) or an equivalent regulation.
2) The project shall not make use of components or services that would limit the participation of the National Aeronautics and Space Administration (NASA) staff or providers as project advisors.
3) The launch provider shall be JAXA.

The first constraint was set in order to avoid any legal issues that might be faced when using components with regulations. The second one relates to restrictions involving NASA staff, since various key members of the project are associated with NASA. Due to the agreement reached between ACAE/TEC and Kyutech, the launch provider must be JAXA.

1.4 Schedule and reviews

Table 2. Irazú project phases 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-April 2017	Critical Design Review (CDR), CubeSat subsystems, ground station components, ground sensors
Phase D: Integration, Testing and Deployment	May 2017-June 2018	Flight Readiness Review (FRR), CubeSat flight model, mission control, ground segment, Operational Readiness Review (ORR).
Phase E: Mission Operations	July 2018-Dec 2018	CubeSat operating in orbit and communicating with remote/ground stations.
Phase F: Mission Disposal	Dec 2018	Final mission report, lessons learned, scientific report.

Table 2 displays the different phases of the mission, their time period and deliverables at the end of each phase. The schedule is divided into seven phases in a similar fashion to NASA's project life-cycle. The Irazú team completed the Critical Design Review at the time of the writing of this paper and is in the process of ordering the spacecraft and ground station components. Development of the spacecraft subsystems will span from August 2016 to April 2017, while integration of the flight model will be done on May 2017 in Costa Rica and shipped on June 2017 to Kyutech for testing. Costa Rican engineers will be in charge of the testing under supervision of Kyutech staff. Parallel to this testing and certification, the Irazú team will be testing the remote and ground stations located in Costa Rica to ensure proper functioning during the mission. From the end of testing of the flight model until the launch date, the Irazú team will prepare for and pass the Flight Readiness Review and Operational Readiness Review. Launch date is planned on July 2018 considering a 6 month-margin for the launch window. The spacecraft will be transported to the International Space Station (ISS) and released from JAXA's Kibo module. After 6 months of operations, the team will close out the project by writing reports on mission results.

Table 2 shows that at the end of each of the first four phases, there is a review that the Irazú team must pass (for Phase D there are two reviews). These reviews are evaluated by an external committee made up of experts in space engineering projects and small satellite design. Table 3 presents the members of the committee and their current role in the aerospace industry or academia.

Table 3. Irazú project external evaluation committee.

Name	Current Role
Dr. Franklin Chang-Díaz	President and CEO of Ad Astra Rocket Company
MSc. Sandra Cauffman	Earth Science Division Deputy Director at NASA
Dr. Andrés Mora	Robotics System Engineer at NASA-Ames
Dr. Mengu Cho	Director of the Laboratory of Spacecraft Environment Interaction Engineering (LaSEINE) at Kyutech
Dr. Eberhard Gill	Director of TU Delft Space Institute
Dr. Gugliemo Aglietti	Director of Surrey Space Center.

1.5 Budget and fundraising

One of the project´s challenges is to design and execute a low-cost mission, due to the limited funds that are available for science and technology projects in a developing nation. Some of the methods that the Irazú team has used to reduce the project's cost are the following:

1) Volunteer work: The majority of the core team of scientists and engineers work as volunteers for the project, such as the mission systems engineer and some subsystems experts.
2) CubeSat model: Only a flight model will be used for the mission. The engineering model is not included due to the low complexity of the spacecraft.
3) Kyutech agreement: Kyutech has agreed to secure a launch opportunity and provide testing services at a reduced price in order to promote aerospace development in Costa Rica.

TEC assumes a considerable amount of the project´s cost, including the scientific component and salaries of the scientists and engineers working on Irazú, among other things. The remainder of the costs, including the spacecraft/ground station components and launch services, had to be secured through external entities, otherwise known as the sponsors. Instead of following a traditional approach of applying for government funds, the Irazú fundraising team, led by ACAE with the support of TEC and EY (a consulting firm and one of the project's sponsors), developed an alternate strategy. This consisted of a two-step approach:

1) Secure funding from regional companies wishing to support the first Central American satellite.
2) Launch a crowdfunding campaign to enable financial support from civil society.

The first step consisted of finding companies from Costa Rica´s private sector that were interested in collaborating either with funding, services or both. In order to make the sponsorship more appealing, an aluminium plate will be placed on one of the CubeSat sides (where a solar panel should be placed) with the logos of the sponsor companies. This means that power generation will be sacrificed in order to secure funding. Fortunately, the spacecraft has low power requirements.

The second step of the funding strategy consisted of launching a crowdfunding campaign using the Kickstarter platform. This would not only help raise money, but also awareness regarding the project. The campaign was launched in March 2016 with a goal of raising $75,000 in 30 days. The campaign surpassed the goal, securing $81,369 [3]. Potential donors were encouraged to support the project by offering rewards depending on the amount of money they donated. For example, backers that donated more than $500, will get their name in an aluminium plate that will be stored inside of the CubeSat.

1.6 Risk management

Although a CubeSat mission seems like a simple endeavour compared to more complex space project, it is always important to consider risks and find ways to mitigate them. The primary tool that the Irazú team used for risk analysis and mitigation was the 5x5 risk matrix presented in Figure 1. A total of 38 risks were identified including project management aspects, such as delays in schedule and lack of funding, and technical aspects, such as failure in antenna deployment. They were organized by likelihood of occurrence and consequence as displayed in the matrix.

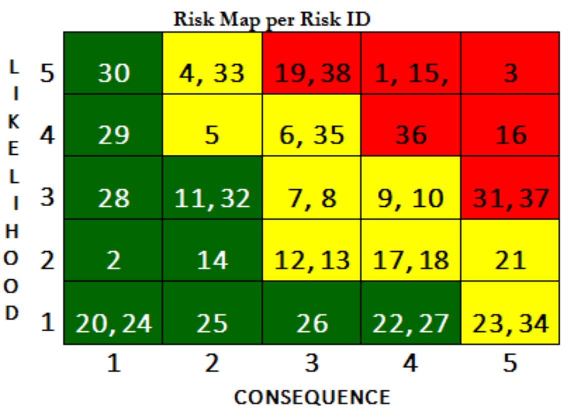

Fig. 1. Irazú project 5x5 risk matrix.

2. Science

The scientific component aims to contribute to ongoing studies to determine the growth of biomass of a tree planting and study the influence of environmental variables. This is important for assessing the environmental services of these ecosystems that fix carbon from the atmosphere. The forest plantations grow evenly, and this condition allows accurate estimates of biomass growth and total carbon fixing. Because the satellite's lifetime will only be 6 months, the scientific team decided to concentrate all their efforts for this mission on the monitoring of growth of tree plantations and to emphasize other aspects, such as to study and understand the hydrology-climate-soil-growth relationships, of the selected species.

This mission will provide the foundation for future development of new proposals on reforestation that offsets carbon emissions. Furthermore, this mission aims to impact directly in the short term the promotion of Costa Rica's forestry sector and to encourage reforestation with commercial timber species.

Given the above, the aim of this mission will also contribute to the country's goal of becoming carbon neutral. The general science objective can be formulated in the following fashion:

To monitor the environmental service of a forest plantation by carbon sequestration and studying the dynamics of biomass growth and its relationship with environmental variables

The scientific mission of this project is framed to respond to one of the most important global threats: climate change. Our project will focus, for the first time, on how tree plantations fix atmospheric carbon on a daily basis and how the rate of carbon fixing is affected by changes in environmental variables. This contribution is relevant, because until now, there have been no studies that have provided data on a daily basis that deals with the mitigation and adaptation of ecosystems under climatic variability due to global change scenarios. Furthermore, the scientific component will contribute to the goal of Costa Rica to become a carbon neutral country by 2100, including a reduction in its carbon emissions of 50% by the year 2050 [4].

To accomplish the scientific mission, three experimental plots (1-year-old) were planted with Gmelina arborea, a fast growing species of trees [5], in the northern region of Costa Rica, thanks to the collaboration of a private company. Inside the experimental plots, a complete weather station will be placed on the top of a tower (15 m). The site also will include several stations to monitor soil moisture at a depth of 10 cm. Several trees will be measured by electronic dendrometers. The forest plantations grow evenly, and this condition allows accurate estimates of biomass growth and total carbon fixing.

Fig. 2. Experimental site in Los Chiles de Alajuela.

This study will be conducted at a property owned by Los Nacientes S.A., located in the province of Alajuela, District Los Chiles, in Northeastern Costa Rica, approximately 17 km southeast of the border with Nicaragua and 25 km southeast of Nicaragua Lake. 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 annual rainfall of 1950-3000 mm. The climate in the region has a highly variable dry season for 0-5 months [6].

2.2 Experimental design and data collection.

Three plots of 500 m2 (20 x 25 m) were established in the selected site. This experimental design offers enough repetitions for an adequate characterization of tree growth rates. Each plot is composed of 40 trees. All trees are being measured every month (diameter at 1.3 m height (DBH) and tree canopy height). Leaf area index for each plot will be monitored by non-destructive techniques (LAI-2000 and hemispherical photography) [7], [8], [9], [10], [11].

The monitoring of daily growth (diameter) will be carried out by placing electronic dendrometers on five selected trees. The five electronic dendrometers will be synchronized with a data aggregator that stores the information. The daily average for the five trees will be transmitted to the satellite. If it is possible technically, the daily data for the five trees will be transmitted individually also.

In the middle of each plot, we will place a tower, which will have two pyranometers (measuring the flux of solar radiation) and two photosynthetic active radiation sensors (measuring radiation between 400 -700 nm). These sensors will measure the incoming energy and the reflected energy by vegetation at intervals of 30 minutes. The information is transmitted to a data aggregator every 30 min. These sensors will be placed at least 3 m above the canopy.

At the top of the tower, a complete weather station will be installed with its own data aggregator with sensors to monitor environmental variables: rainfall, relative humidity, temperature, barometric pressure, wind direction, and wind speed. In addition, the tower will be used to install the antenna for the satellite data transmission system, solar panels and data aggregators. At the bottom of the tower, three sensors will be installed 10 cm deep to monitor soil moisture.

2.3 Dendrometer design

The electronic dendrometer is intended to measure variations in tree diameter every day without strangling or inhibiting tree growth, therefore, the device must have a single point of contact with the tree. The measurement of diameter should be within 0.1 mm precision, and requires a wireless transmission mechanism to carry data from the dendrometer to the aggregator (data logger). Currently, the scientific team is in the phase of final design of developing and calibrating this sensor.

2.4 Ground instrument integration

At a central point to the plot where all measurements are collected, the team is designing a basic data-logger (named Eco-logger) that will control two main tasks:

1. Collect all data from remote sensors (i.e., dendrometers, weather station, and soil moisture station).
2. Pack all collected information in a single data packet that is ready to be transmitted to the satellite relay.

The Ecologger is a microcontroller-based device, which holds a repetitive software pattern to measure certain variables and poll data from remote sensors at a configurable frequency. In addition, the Ecologger holds a precise time base, 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 in the event that communication to the satellite is lost. It also has a backup communication interface using a USB protocol, which can be used to connect to a different transmitter, or to use ground-based communication technologies, if required.

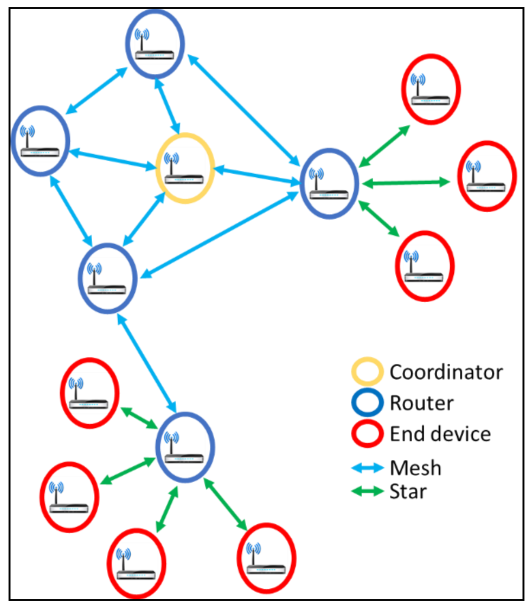

Fig.3. Wireless transmission network

On the communication interface, the Ecologger acts as a data aggregator, which supports an XBee master node, which is able to collect information from all the remote dendrometers (Fig. 3). These data are merged to the previously described sensors, packed as a single data transmission unit, and prepared for transmission. After the satellite communications module is ready (and the CubeSat is on orbit), the data relay service will be started. Meanwhile, the Ecologger supports a secondary storage system that uses an SD card and enables a serial communication interface (USB), which allows data retrieval from the unit. It also operates using a battery, which enables installation from a remote location. It has yet to be adapted to a solar charging system to extend battery life and system autonomy.

3. Mission overview

The main goal of the Irazú mission is the following:

To develop a full life-cycle space engineering project using CubeSat technology as a proof of concept of a communication platform able to transmit environmental measurements from remote areas in Costa Rica's territory to a data visualization center for research on carbon fixation.

From the objective, one can observe that Irazú will address two of the country's needs: the measurement of environmental variables and the development of a space project. The former is essential to Costa Rica since 53% of its area is covered by rainforest [12]. The country places a high priority in forest conservation. Additionally, the Irazú measurements will contribute to the goal of becoming carbon neutral. Irazú also seeks to develop a cadre of highly skilled individuals in the development, integration, testing and operations of space missions. By developing these skills, Costa Rica will enable future missions to help solve other of the country's needs. The mission's objectives can then be defined as:

1) To establish a space platform with which Costa Rican scientists can efficiently retrieve otherwise difficult to gather data.
2) To train a Costa Rican team of engineers and project managers that will use standard aerospace development techniques and procedures to encourage the country´s insertion into the global space industry.
3) To develop Central America's first successful space mission with limited budget and resources.
4) To demonstrate and lead Central America's insertion into the space industry through the use of existing *CubeSat* technology, due to its maturity level and cost accessibility.

The concept of operations (ConOps) describes the segments of Irazú and how they interact and operate. The mission consists of three main segments: the remote station segment, the flight segment, and the ground segment. These are presented in Figure 4 and a brief explanation of each of them is presented below:

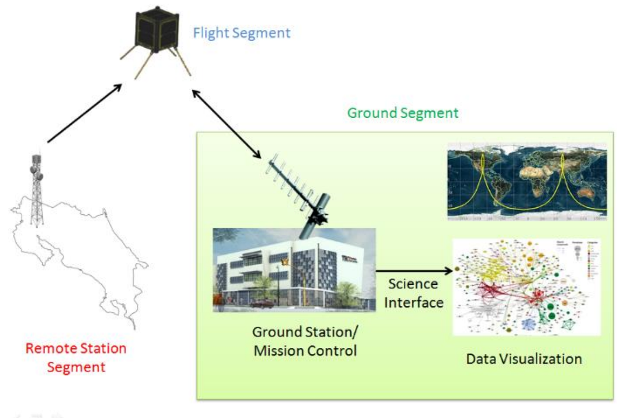

Fig. 4. Irazú project concept of operations.

1) **Remote station segment:** This is where the measurements take place. Here the sensors will be used to measure tree diameter growth, temperature, humidity, rain, wind direction, air pressure, and soil moisture, among other variables. TEC already uses some of these measurement nodes and we will be developing more in the future. TEC will also develop a platform that is capable of centralizing data from all sensors in a particular region and transmitting these data to the space segment.
2) **Flight segment:** The segment consists of a satellite that will collect the data generated by the sensors and transmit it back to a central location using a satellite-to-ground communication standard platform.
3) **Ground segment:** The Irazú team will build the ground station in TEC, which will include a mission control component. The ground station will provide the retrieved data to a scientific data analysis and visualization system, providing the sensor readings to scientists to further their research on carbon fixation.

The satellite will be a proof of concept of an orbital data relay system for information sent between ground based measuring stations and a data gathering, analysis and visualization ground station.

4. Spacecraft

The design of the CubeSat in Irazú has considered one important factor; given that this satellite is the first one built in the country (and all of Central America), the failure of its mission would have a deep impact in the feasibility and marketing of future missions. Nevertheless, in order to comply with the requirements of the missions related to the participation of the Costa Rican team in the design and development of the system, and in more general terms, showing the local capabilities to work on a space mission, a compromise on the design has to be taken. In order to balance both objectives, the design team has taken the following approach:

1) Design the critical parts of the CubeSat using systems with a TRL of 9, meaning that they have been flight proven during successful mission operations. By doing this, the team is considerably reducing the risk involved in the design, and not requiring an engineering model of the system.
2) Manufacture the 1U CubeSat structure in Costa Rica, by an experienced company. Given that the structure is already defined by the CubeSat standard, and that there already exist companies within the Costa Rica Aerospace Cluster with the capability of building structures according to the requirements, it is possible to get this subsystem built within the country, and thus minimizing the risk involved with the mechanical subsystem.
3) Design and construct a non-critical system in Costa Rica. This allows Costa Rican engineers to familiarize themselves with the process of implementing a flight system. At the same time, risk is managed by not making this system critical.

These three actions aim to considerably reduce the risk, while allowing the Costa Rican team to acquire experience in design.

4.1 Spacecraft systems engineering

The spacecraft is divided into 6 subsystems, as presented in Figure 5. The first five (structure, thermal, electrical power system (EPS), onboard computer (OBC) and communication) are essential for any CubeSat mission, while the payload is usually reserved for the scientific component. Since the Irazú project has its scientific component on the ground, the payload was used for educational purposes. A secondary OBC is being developed by Costa Rican engineers to act as an Inertial Measurement Unit (IMU), but mainly to provide these engineers the experience of designing, manufacturing, testing and operating a spacecraft component. One notable absence in the design is an attitude control system (ACS). Since the spacecraft has an antenna with a omni-directional pattern and since it lacks a scientific payload with pointing requirements, then an ACS is not necessary for spacecraft operations.

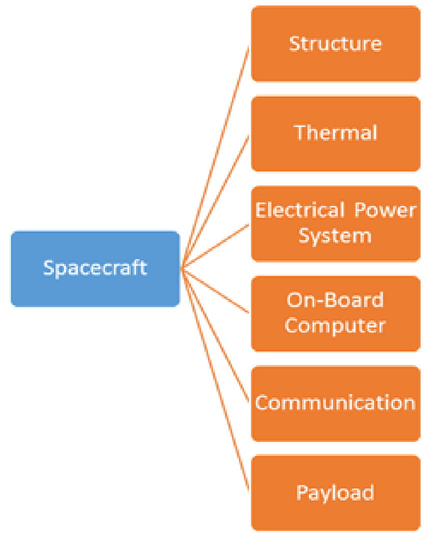

Fig. 5. Irazú CubeSat subsystems.

The architecture of the CubeSat is presented in Figure 6. It follows a decentralized approach that comes standard in the GomSpace CubeSat platforms [13]. Each subsystem has its own microprocessor that connects to the bus using either I^2C or CAN (for the Irazú spacecraft, I^2C will be implemented). Additionally, the GomSpace SDK and mission libraries will allow the team to program the spacecraft functions. These will be used in order to ensure rapid development of the subsystems and to lower risk, since they have already been used to successfully develop other GomSpace CubeSats.

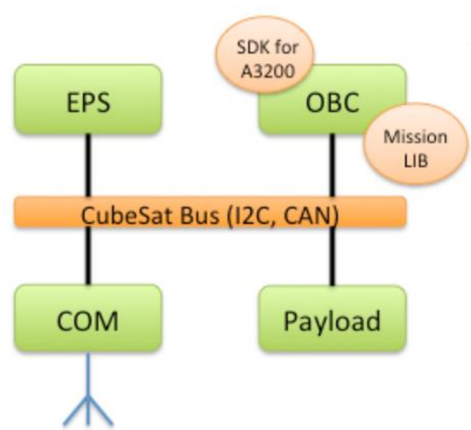

Fig. 6. Irazú CubeSat architecture [13].

4.2 Spacecraft subsystems

The Irazú CubeSat design is similar to the 1U platform offered by GomSpace with the following differences:

1) The CubeSat structure is manufactured in Costa Rica.

2) The payload is a secondary OBC which acts as an IMU.
3) An aluminium plate is placed on one of the sides of the CubeSat and another one inside of the spacecraft for fundraising purposes.

An exploded view of the spacecraft is presented in Figure 7. The GomSpace subsystems were selected since they satisfied all the requirements that were defined in project Irazú's SRR. Furthermore, only one supplier was selected for the critical electronic components to facilitate the integration process.

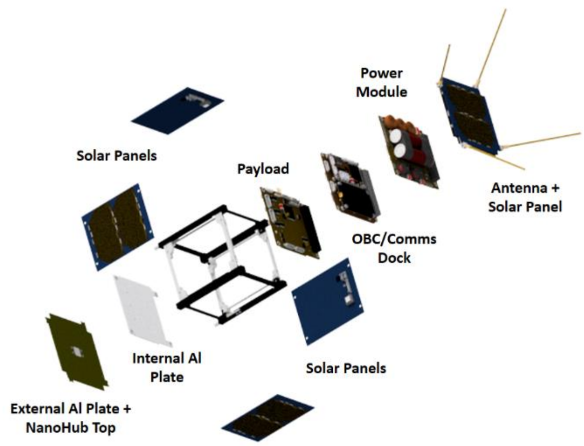

Fig. 7. Irazú CubeSat exploded view.

The EPS consists of 5 solar panels, that can generate up to 2.3 W in LEO, and the power supply, consisting of a 7.4V battery. The communication system is half-duplex operating in UHF with an omnidirectional canted turnstile antenna. The GomSpace OBC includes an AVR32 MCU and an attitude determination system, consisting of 3-axis magneto resistive sensor and 3-axis gyroscope. The other subsystems included in the spacecraft are thermal and structural. For these, an extensive analysis had to be performed in order to conclude whether the CubeSat will survive the launch and operating environment.

5. Ground station

The ground segment is the final component of the Irazú mission. Its functions are tracking the satellite, monitoring its health, uploading commands and most importantly downloading the data that originated from the forest sensors. The ground station was designed by the Radio Club of Costa Rica, using recommendations from M^2 Inc., which offers solutions for amateur radio satellite ground stations. The main objective was to create a low-cost station for operations in the UHF band. This can be accomplished by using Commercial Off the Shelf Components (COTS). The ground segment is composed of three elements, which are:

1) Ground station
2) Mission control
3) Data visualization

The ground station component relates to the actual hardware required to contact the spacecraft, while mission control focuses more on the software needed to operate the mission. The final element of the ground segment is used to turn the raw data acquired by the ground sensors to produce scientific imagery that will be attractive to the public and raise interest in the mission. Figure 8 displays the block diagram of the ground segment.

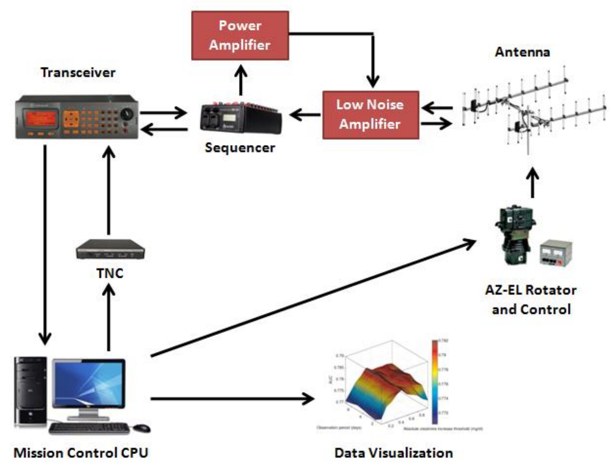

Fig. 8. Block diagram of Irazú ground segment.

Table 5 presents the components of the ground station, the selected models for the design and the distributors that sell them. The Radio Club of Costa Rica suggested M^2 Inc as the main distributor since they have purchased and operated their products and have had good experience with this company in terms of delivery and product support. The Yaesu rotator control model was selected due to its ease of use over the one offered by M^2 Inc. Furthermore, the Kenwood TS-2000 transceiver was selected since it has a built in terminal node controller (TNC) and power amplifier, among other features.

Table 5. Stakeholders of the Irazú project.

	Distributor	Model
Yagi UHF Antenna	M^2 Inc	FGCBLEOPACK
Az-El Rotator and Control	Yaesu	G-5500
Low Noise Amplifier	M^2 Inc	2M-PA 2M
Sequencer	M^2 Inc	S3
Transceiver	Kenwood	TS-2000

6. Lessons learned

There have been considerable advances in the Irazú project, not only in the technical and scientific aspects but in fundraising and infrastructure as well. The lessons learned up to this point are detailed in this section. These can be applied to any entity developing their first space mission. They are presented in the following subsections.

6.1 Design a feasible but relevant mission

The Irazú project has gone through various iterations regarding the design of the mission [14], [15]. The constant criterion has been that the scientific component should address one of Costa Rica's needs, providing a solution that can be used for the benefit of the country. Many developing space nations use their first mission as an educational experience to create the capabilities required to execute further space related projects. The downside of this approach is that it will be difficult to create a sustainable program if there is no clear benefit to the country. The scientific component of Irazú will provide publishable and applicable results that will aid in Costa Rica's goal of becoming a carbon neutral entity. Using this approach, the Irazú team envisions future missions with more ground sensors and a more robust spacecraft that will collect data for years.

6.2 Create a strong infrastructure

The infrastructure consists of all the stakeholders participating in the project from government, academia and the private sector. This is the foundation of the project and with a weak foundation, progress will be extremely difficult. Not only will it be used for the current space mission, but it could facilitate the beginning of future missions since the key stakeholders for executing this type of project have already been identified. The first step in building the infrastructure, is creating the core team which consists of scientist and engineers that will be designing, developing and executing the mission. The core team may not have the capacities required for these tasks but these may be acquired through training or guidance from experts in the field. For Irazú, the external committee presented in *Section 1.4* of this paper was created to evaluate the work of the team at each stage.

A common misconception in developing space nations is that organizations with the required capabilities to contribute in space missions are non-existent in their countries. The reality is that some of them have the necessary skills but have not been exploited yet. An example of this from Irazú is a precision manufacturing company called Atemisa. They specialize in creating components for the medical industry and were able to easily manufacture a 1U CubeSat structure. Another example is the RCCR, the amateur radio society of Costa Rica which already had experience contacting spacecraft in the amateur radio band even before the project had initiated. Identifying these organizations will facilitate the progress of the project through the use of their skillset.

Furthermore, there may be some product or service that might not be feasible for a developing nation. Two examples from the Irazú project are the testing and launch of the spacecraft. Costa Rica does not have the equipment required to perform all the tests for the certification of the CubeSat and does not have any launch capabilities. This problem was resolved by seeking for international collaboration. Kyutech, one of the key partners for the project, will assist the team in certification of the spacecraft and coordinate with JAXA to provide launch services.

6.3 Keep it simple

For the first space mission of any entity, there will always be a high level of technical and administrative difficulties. Since failure cannot be an option, one must always try to keep the mission as simple as possible without compromising the main objectives. One method that has been used to accomplish this at an international level is the use of the CubeSat standard. It was created by Prof. Jordi Puig-Suari and Prof. Robert J. Twiggs in order to meet an educational need to develop small, low-cost satellites in a short period (1-2 years) with a reduced launch cost [16]. The standard was originally envisioned for educational use only, but it allowed developing nations with limited budgets to execute full life-cycle space missions. The Irazú team selected this standard to simplify the flight segment. Moreover, since it is international and there is a worldwide community using CubeSats, it opens up the opportunity for international collaboration as was the case with Kyutech for this project.

6.4 Identify risks and create a mitigation strategy

For any project there are going to be risks and it is important to identify them and find ways to mitigate them from the start. This will be a continuous process since more risks will be identified as the project progresses. The most common ones are delays in the schedule and unexpected expenses that modify the budget. It is important to plan with margins for both of these.

When it comes to spacecraft design and development, the Irazú team decided to use COTS with a TRL of 9 in order to reduce the risk of the flight segment. Proven subsystems are essential for the design of a spacecraft, especially for the first mission. The decision of purchasing them instead of constructing them help reduce the risk but at the same time gives the engineers working on the project a chance to familiarize themselves with the operation of the subsystems in order to learn how to develop them for future missions.

Another example of how the risk of the flight segment was reduced was the decision to have the scientific instruments on Earth instead of on the spacecraft. Most CubeSats used for Earth observation are designed to have a payload which collects data [17]. This increases the risk of the spacecraft since it increases its mass, power demands and volume requirements. Furthermore, if the instrument fails there is no way to fix it once the spacecraft is launched. With the Irazú approach, this is mitigated by having the ground sensors transmit the data to the spacecraft.

6.5 Develop a fundraising strategy

A common problem when attempting to execute a state of the art science or technology project in a developing nation is securing funds. For Irazú, an innovative strategy was created in order to secure the resources necessary to complete the project (a description of this strategy is presented in *Section 1.5*). It is important to remember that government funding is not the only option for space missions. Crowd-founding platforms such as Kickstarter or Indiegogo are viable options which will not only help in obtaining funds, but provide media exposure to the project and support from the civil society as well. Donations from private companies are an alternative. Both of these were implemented in Irazú with successful results.

7. Conclusions

There are many challenges in advancing a small satellite mission in a developing country and the Irazú project is no exception. Various milestones have been achieved over the last year and a half, including the successful completion of the MCR, SRR, PDR and CDR, but there still remains arduous tasks ahead. The next steps include the acquisition of the CubeSat components to begin development of the flight segment, the implementation of the ground sensors in the experimental site and the development of the communication segments of the mission, among other things. The keys to the success of the project so far are shared in this paper so other developing countries wishing to design, develop and execute their first mission can use them as guidance on their future endeavour.

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