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# New opportunities offered by Cubesats for space research in Latin America: The SUCHAI project case

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## Abstract

During the last decade, a very small-standardized satellite, the Cubesat, emerged as a low-cost fast-development tool for space and technology research. Although its genesis is related to education, the change in paradigm presented by this satellite platform has motivated several countries, institutions, and companies to invest in a variety of technologies, aimed at improving Cubesat capabilities, while lowering costs of space missions. Following that trend, Latin American institutions, mostly universities, has started to develop Cubesat missions. This article describes some of the Latin American projects in this area. In particular, we discuss the achievements and scientific grounds upon which the first Cubesat projects in Chile were based and the implications that those projects have had on pursuing satellite-based research in the country and in collaboration with other countries of the region.

*Keywords:* Cubesat technology; Microgravity; Ionospheric–magnetospheric measurement

## 1. Introduction

Since the Sputnik changed history in 1957 by being the first artificial satellite launched into space, research and technology in these areas continues to evolve. In the early years of space missions everything was developed for the sole purpose of military information and with huge budgets (Peter, 2006). However, by the end of the cold war a new principle was established: "Faster, Better, Cheaper" (Watzin, 1999), where the premise was to reduce the developing time as well as to design, construct and launch satellites by using commercial parts. Despite its simplicity, this idea had great impact on space projects. However, even with this philosophy in mind, emphasis was still placed on the vehicle instead of the payloads or instruments. In that sense the vehicles (satellites and rockets) needed to adapt to the best possible payload with the longest possible operational time. More recently, an international trend has emerged, related to the standardization and use of very small satellites (nano-, pico- and femto-satellites) in space science, where the Cubesat standard dominates. Initially conceived in 1999 as an educational tool (first launched in 2003), in less than a decade the

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Cubesat standard has become suitable for space research. Beyond the small size, the main philosophical change is, that in this approach, emphasis is placed on the payload, and thus the payload has to adapt to standardized vehicles (Cubesats and piggyback deployment systems). This produces a huge reduction of the costs/time of manufacturing and launching a satellite which are by far the most expensive part of the space research endeavor. The utility of Cubesats as scientific research and technology validation platforms is now increasingly recognized (Jones, 2014). The new capability offered by the Cubesat is promising to catapult the interest and collaboration of Latin America in space research (Woellert et al., 2011). The miniaturization trend has also revitalized the concepts of PCB- and Chip-Sat, satellites that fall into the femto-satellite category ($< 0.1$ kg) (Barnhart et al., 2009; Manchester et al., 2013). This trend could facilitate a massive space sensing network concept at very low budgets.

Latin America has not been indifferent to this development and some Cubesat projects have already been launched. Colombia was the pioneer in this area with its Libertad I 1U Cubesat launched in 2007 (Woellert et al., 2011), and other countries/missions followed. These include Ecuador with NEE 1 and 2 (launched in 2012 and 2013); Peru with PUCPSAT, launched in 2013 and CHASQUI UNI (Canales et al., 2010), launched in 2014; Brazil with NanoSatC-Br1 launched in 2014 (Vargas-Cuentas and Roman-Gonzalez, 2014); and Uruguay with AntelSat in 2014 (Tassano et al., 2014). Argentina has also launched a couple of Cubesats as a private–public initiative. There is a larger list of Cubesat projects currently holding for launch and/or under development. This is the case for the first Chilean Cubesat project, the Satellite of the University of Chile for Aerospace Investigation (SUCHAI). This project is the seed to a much longer program at the University of Chile, which will be carried out by the Space and Planetary Exploration Laboratory (SPEL). Our main objective, as a research group, is to explore the possibilities that this standard can offer to countries with limited budget for space research in order to enhance this area in Latin America.

The SUCHAI project consists of a 1 unit (1U) Cubesat already scheduled to be launched in mid 2016. Two more Cubesats have been approved within the Laboratory for construction during the next three years. The second and third Cubesats will be 3-unit (3U) Cubesats. With these coming missions, we expect to contribute in space modeling by combining in situ measurements, made with nanosatellites, and ground-based instruments, which will lead to better magnetospheric/ionospheric parameter estimation. Our group has experienced the huge opportunities this standard can offer in the fields of education, technology development and science. This is true in particular for space, which could be of special relevance for groups and countries without much history/experience in satellite technology. In the following sections, we describe some of the achievements and grounds of our space program.

## 2. SUCHAI project

SUCHAI is a 1U ($10 \times 10 \times 10\ \text{cm}^3$) Cubesat, developed at the SPE Laboratory. The program started in 2011 with a budget close to USD 200 K, which included setting up the Laboratory, salary of an engineer, construction of 1U Cubesat, vibration and thermal tests, and the launch. The SUCHAI Cubesat carries (1) a simple Langmuir probe, (2) a small camera, (3) an electronics-in–hostile-environment experiment and (4) a battery health management experiment. It also contains monitoring tests for other electronic/mechanic components and the flight software. Currently, the SUCHAI has passed independent vibration and thermal tests at LIT-INPE facilities (Brazil) in May 2014 and is expected to be in orbit early 2016 (See Fig. 1).

The Cubesat SUCHAI will be launched in a Space-X Falcon-9 rocket and will have a polar elliptical orbit 700 km × 400 km. The Cubesat is expected to operate in coordination with ground-based instruments such as magnetometer networks and Incoherent Scatter Radars (ISRs). Its Langmuir probe will measure the plasma density at low orbit at all latitudes. These measurements will be combined with GPS scintillation and TEC measurements by ground-based magnetometer and GPS networks placed in Chile. In addition, the satellite will be used in coordination with Incoherent Scatter Radars (ISRs) to study the improvement, from the point of view of information theory, in the estimation process of ionospheric plasma parameters. Technology motivation around the platform (software, deployment, communication, structural, control, thermal and energy systems) and the instruments (magnetometers, Langmuir probes, radio beacons, and GPS) have been excellent drivers not only for technology research, but also for the possibilities of performing research in space physics.

In fact, the latter has also motivated the Chilean space-physics community. The high impact that this platform is already having in a country like Chile with relatively small current space-technology development can be exemplified by highlighting that Conicyt, the main research agency of the country, has already approved two more projects to build the second and third scientific satellite to be developed in Chile, this time two 3U Cubesats. Both, the SUCHAI satellite and the coming Cubesat projects have, and will focus on performing research not only in the platform, but also in space science. In addition, the collaboration between SPEL and Jicamarca Radio Observatory in exploring the possibility of measuring TEC by using radio beacons at different frequencies, as explained further later in this document, is an example of the possibilities that these types of projects can offer within the region.

## 3. Research focused on Cubesat platform

The space vehicle is a relevant driver of technology research. Studying and developing new technology/techniques might facilitate other applications of Cubesats in

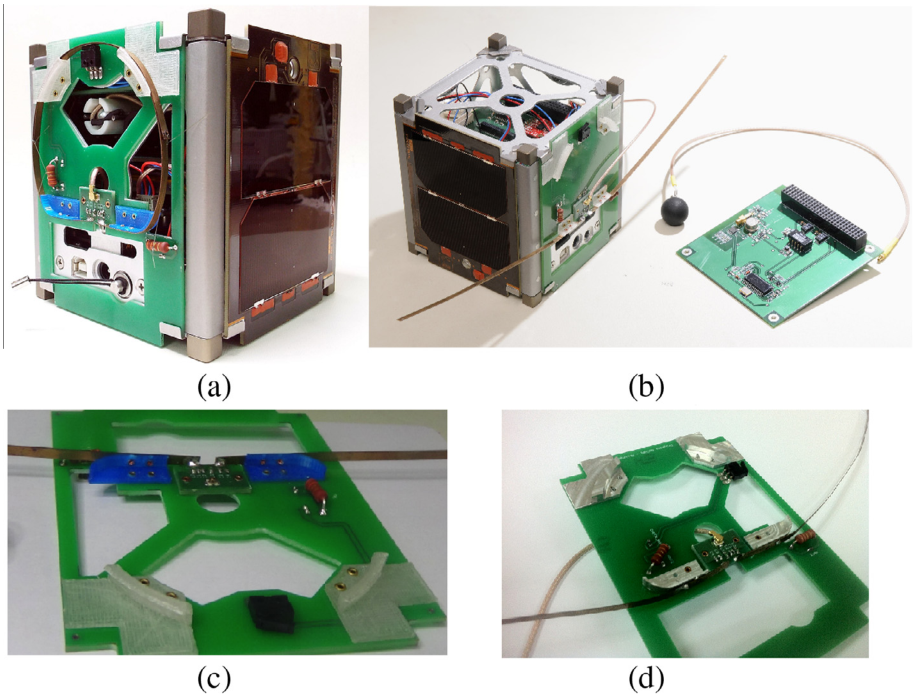

Fig. 1. (a) SUCHAI Cubesat, (b) the SUCHAI Cubesat next to the PC104 board and spherical probe of the Langmuir probe, (c) antenna deployment system with parts made of plastic with a 3D printer and (d) antenna deployment system with parts made of duraluminum made with the FabLab CNC.

the near future. In this section, we present a discussion of the motivation of the platform research of our coming projects.

### 3.1. Digital fabrication and Cubesats

For the SUCHAI project digital fabrication tools, like those present in Fab Labs (Gershenfeld, 2008), have proven to be of great value. However, the impact of these tools goes beyond the satellite itself (Mardones et al., 2012). The digital fabrication tools are becoming less expensive and yet more powerful. They have the potential to diminish the barriers of entry into the complex field of aerospace development. Recent studies (Mardones et al., 2012; Gutierrez et al., 2011; Piattoni et al., 2012) have been done based on state of the art digital fabrication tools for rapid development and testing of either laboratory equipment or actual functional parts that will be carried to space by aerospace designs. These types of tools not only allow rapid design and prototyping, but also increase the possible number of collaborators. With Computer Aided Designs (CAD) software, some of them open source and freely available, the designs can be shared. By sharing the CAD designs via Internet, remote design can be performed (e.g. by other universities and school students). The designs can be built in Fab Lab facilities and feedback on performance of the design and can be later delivered to the actual designer(s). NASA is currently carrying on an experiment for testing a 3D printer in microgravity conditions, in particular within the ISS (Snyder et al., 2013). Microgravity is relevant but the vacuum-high/low temperature effect is relevant as well, since possible exploration missions can be done in the future with devices that can repair themselves in some hostile environments. The focus of digital fabrication for our laboratory is accordingly related to rapid and better fabrication, but also studies the idea of printing or fabricating in space. The work will concentrate on digital fabrication tolerant to space conditions, which ultimately might catapult CubeStas from a Commercial-Off-The-Shelf (COTS) aerospace philosophy to an Open Hardware (and highly collaborative) aerospace philosophy. For instance, although (Piattoni et al., 2012) reports good tolerance to vibrations of Cubesat structures made of ABS, tests within the SUCHAI project have found that parts made of ABS plastic suffer deformation under conditions when vacuum and high-thermal gradients are combined. Parts of SUCHAI made of ABS responded well for independent tests (vacuum or high temperature), while deformation was evident for a combined test. The final parts were done in duraluminum with another digital tool, a CNC (See Fig. 1). Besides the response of our parts to these tests, it is important to notice that the designs are open and easily reproducible with FabLab machines, accelerating the starting point of other groups providing eventually a number of possible improvements to the original design.

### 3.2. Hostile environment electronics as a part of our Cubesat platform

Electronics are the main resource for automation, control, data acquisition and processing, AC/DC conversion, and so forth. In laboratories, ad hoc electronics are used to pursue specific features of experiments which are highly nontrivial. However, electronics can be used as an experimental facility itself. To wit, the first transistor (Bardeen and Brattain, 1948) was devised as one of the main experimental achievements in science and technology of its time, although nowadays, any personal computer has billions of them. Other electronic systems have been constructed to probe new physics. Stochastic resonance has been studied using diodes (Fauve and Heslot, 1983), chaotic behavior (Chua, 1980), and non equilibrium power fluctuations has been studied using linear circuits (Douarche et al., 2006), to mention a few. Additionally, these experimental electronic setups are expected to be more prominent as nano electronics and single molecule electronics grow (Petty et al., 1995). In this context, the control and characterization of the hostility of the environment on electronics is of paramount importance in particular when considering environment strains and attacks on normal behavior of electronic components by the interaction of its parts with its surroundings. As a matter of example, the electronic control system of AURIGA (*Antenna Ultracriogenica Risonante per l'Indagine Gravitazionale Astronomica*), an ultracryogenic resonant bar experiment to measure gravitational waves, displays non equilibrium behavior in an extreme environment of low temperature and large power fluctuations (Bonaldi et al., 2009).

Outer space is an example of a hostile environment for electronic circuits forced out of equilibrium. There is no radiative heat transfer, no shielding to magnetic or electric fluctuations coming from EM radiation, and no temperature control for the low–high temperature cycles. Thus, our Cubesat platform is an excellent candidate to perform hostile environment studies for electronics. Simple commercial parts can be used to construct an electronic circuit whose functionality can be tested in such an environment. Data acquisition is straightforward and power consumption is as low as desired. Some difficulties arise (i) when higher power is needed, as the regular Cubesat platform cannot provide power larger than a few watts per function, and (ii) in the case when large data sets need to be acquired, stored, treated and sent back to Earth. Even so, it is not difficult to prove different features of out of equilibrium systems using electronic circuits even when Cubesat restrictions are taken into account.

Indeed, a simple series RC circuit driven out of equilibrium by a random voltage is already installed in the SUCHAI platform. Commercially available parts are mounted in a small PCB, where the pseudo random driving voltage $\zeta(t)$ with a cut-off frequency $f_c$ and the output voltage at the capacitor $U(t)$ are sampled and stored in the Cubesat on board computer, which is based on a PIC microcontroller. Different data acquisition runs are performed as $f_c$ is changed. The statistics of the injected power into the system $I(t) = \zeta(t) \times U(t)/R$ are computed via its normalized histogram for each run. The normalized histogram in the case of pseudo-random forcing displays two exponential asymmetric tails with a cusp at $I = 0$ (Falcón and Falcon, 2009), which depend on the energy dissipation mechanism of the electronic system. Thus, a simple system like this one can show how power fluctuations are inherently coupled to characteristics of the surrounding a hostile environment.

For the coming missions of our group, a new setup to measure the injected power into a nonlinear circuit in a hostile environment is being designed. As presented by Bonaldi et al. (2009), a nonlinear circuit loop can serve to measure and control how an electronic system depends and adapts to a hostile environment. A simple prototype system proposed for mounting in our next Cubesat project is a series LRC circuit with a transistor (a MOSFET) or a photodiode serving a nonlinear element changing either the effective capacitance or resistance of the circuit. In this context, the nonlinear LRC circuit response will highly depend strongly on the coupling of the physical properties of the transistor or photodiode to the hostile environment that surrounds the satellite. Similar procedures to compute injected power statistics as used for the previously described linear RC circuit are going to be used, although simpler computations can be performed. Thus, these new configurations are natural upgrades of the current setup already in place in SUCHAI, and these procedures to our knowledge have not yet been tried in Cubesats.

### 3.3. Prognostics and health management

Although some limitations exist for high resolution and sensitivity instruments in the Cubesat standard, the potentialities of the standard are nevertheless evident in the possibility of using larger numbers of Cubesats (dense constellations). Thus, these configurations can compensate for the diminished features of the instruments with measurements with better spatial and temporal resolution. Extreme approaches have been conceived in order to lower the costs and development times of Cubesats to exploit the advantages of large constellations. For instance, Planet Labs, a private company dedicated to Earth observation, has developed a large Cubesat network exploiting the idea that replacement might be cheaper and/or more efficient than making designs more robust (Boshuizen et al., 2014). Under this approach, satellites are developed with more modern technology (similar to smartphone technology) without much verification and testing, which means that operation is not guaranteed based on the space performance knowledge of the selected components. Although this example is extreme, it presents a viable possibility for scientific constellations. The possibility of using more powerful components and systems but with less verification might be used in Cubesats, particularly where the cost of the platform and launch might be comparable to the costs of tests and modification of the design. This could be done by using more robust components, which could imply larger sizes, weight and/or costs. Thus, under the logic of large constellations, the necessity of monitoring new components is of significant relevance. But collecting information about the performance of components is not enough, and therefore it is imperative to develop algorithms using that data to predict failure and estimate the optimal replacement time of a specific Cubesat within the network.

Prognostics and Health Management (PHM) is an approach to system life-cycle support that seeks to reduce/eliminate inspections and time-based maintenance through accurate monitoring, incipient fault detection, and prediction of impending faults. Prognosis may be understood as the generation of long-term predictions describing the evolution in time of a particular signal of interest or fault indicator, with the purpose of estimating the remaining useful life (RUL) of a failing component/subsystem. In particular, novel PHM approaches have been studied and applied to battery technology with a strong emphasis on electric vehicles within the group (Orchard et al., 2012; Orchard et al., 2015; Olivares et al., 2013). In this scenario, a Lithium-ion (Li-ion) battery is assumed to be discharged "completely" before a recharge process. However, this is not the scenario in a satellite or, in particular, for Cubesats. The satellite can be charging the batteries at the same time as consuming power (during sun radiance), the environment conditions are much more hostile (vacuum, high temperature variations with period of low temperature and radiation) and the batteries can be Lithium-Polymer (LyPo).

SPEL is so the development of novel prognostic frameworks that entail information about environmental stresses (temperature, pressure, etc.) and process control variables (load, voltage, current). In this context, within SPEL a series of investigations are underway for the improvement of prognostic algorithms based on either first-principles (physics and chemistry of Li-ion and LiPo batteries) or/and statistical knowledge of the system. Within the SUCHAI Cubesat, the Lithium-ion battery of the satellite has been tested in the lab and will be constantly monitored in space in order to gain information about its behavior and compare it with existing earth behavior models. Model-based/data-driven approaches to failure prognosis that rely both on degradation models of the failing component and sequential Monte Carlo (SMC) methods for state estimation (a.k.a. particle filtering) are being explored. This type of approach takes advantage of real-time measurements, as well as updating model and stress parameters to project system evolution into the future. The work will be focused on the characterization of degradation processes in electrochemical devices, e.g., the prognosis of both the state-of-health (SoH) and state-of-charge (SoC) of lithium batteries that are used in satellites, considering a probabilistic characterization of charge/discharge profiles. For this purpose, we plan to use newly acquired databases, as well as prior information on the most critical fault modes of these systems. Enabling technologies include Bayesian nonlinear filtering techniques for uncertainty characterization, Markov chains for the representation of loading operating profile, kernel-based and computational intelligence methods for model identification, and artificial evolution for model parameter estimation. We also plan to extend this research to decision-based approach as applied to problems where the characterization of the system uncertainty can lead to efficient risk management strategies.

## 4. Research focused on space physics

In addition to technology research, the Cubesat standard offers many possibilities within science. The world is actively working in a number of research areas related to the geosciences (Selva and Krejci, 2012), astronomy, microgravity, space biology and of course space physics (Bahcivan et al., 2014; Jones, 2014). In particular, SPEL is focusing on two topics within space research: *microgravity experiments* and *instrumentation and science for Earth's magnetosphere-ionosphere*. In the following we discuss our objectives and the technology strategy for the instruments we need to build to accomplish the scientific goals.

### 4.1. Microgravity experiments in Cubesats

Microgravity ($\mu g$) environments are constructed to eliminate the effect of gravity $g$ (up to some hundred parts of a million of $g$) in order to perform experiments where $g$ is not wanted or where its effect is detrimental to a specific system under study. Micro gravitational environments are based on free fall of the platform used to generate a $\mu g$ environment with respect to Earth.

The history of controlled $\mu g$ experiments starts with the early drop tubes where $\mu g$ experiments where performed, mainly related to drop dynamics of projectiles. The typical time where $\mu g$ is achieved was of the order of 1 s in very restricted configurations, although issues of power consumption of the experimental device, size, and aspect ratios were of minor importance. Design of such experiments was restricted to the availability of facilities where the longest $\mu g$ runs could be achieved.

As shuttles and airborne vehicles started to provide access to sub-orbital spaceflights, experiments were then constructed that could fit into their tight compartments and restrictive power-consumption schedules. Sounding rockets from different agencies around the world such as the Mini-Texas 5 (a Nike Improved Orion from Sweden) or the first shuttles of the Ariane program from France served as $\mu g$ environments, carrying setups of different sizes, shapes, power-consumption (always below 1 W) and objectives. In these environments, automation of data acquisition, system workflow and operational loops were the main concerns in the design of experiments. The typical time where $\mu g$ was achieved depends strongly on the typical orbit of the sounding rocket, but ranged between 1 and 20 min.

In between these environments, specially modified planes such as the A-300 Airbus Zero-G from Novespace/CNES (Bordeaux-Mignac, France) or the Boeing 727–200 from Zero Gravity Corporation (USA) appeared as an environment option to perform $\mu g$ experiments by conducting parabolic flights at commercial altitude. The typical time where $\mu g$ was achieved depends on the maximum speed that the plane can sustain, but ranged between 1 and 20 s. Power consumption was regulated via the plane's internal power supply, which could generate per experiment up to 440 W on average.

The most desirable $\mu g$ platform is the International Space Station (ISS) orbiting around the Earth at 400 km, where typical fluctuations of $\mu g$ (called $g$-jitters) are less than $10^{-4}g$. In this environment, $\mu g$ is achieved constantly. The power supply of the ISS is 84 kW, provided by solar power.

In Latin America, proper platforms to generate micro gravitational environments are currently very scarce and at times nonexistent. To our knowledge, the only official platform in the context of $\mu g$ experiments was Ecuador's T-39 Sabreliner Fuerza G-1 Condor, performing parabolic flights of 5–10 s. To the best of our knowledge, no other official $\mu g$ Latin American platforms are known in the literature.

As stated above, the amount of platforms capable of sustaining $\mu g$ environments is large. A defining variable that one must take into account in order to choose one or more of these platforms is their costs. We note that each one of these existing platforms needs facilities (shuttles, rockets, planes) and equipment (control towers, fuel) that are expensive, even for large countries with an extensive space exploring history. In this context, small satellites, specifically Cubesats, are new platforms that can outperform the usual and established ones. In Chile, the SUCHAI Cubesat is an example where a novel $\mu g$ environment can be constructed. In a Cubesat orbiting at a 400–700 km polar orbit (such as SUCHAI's programmed orbit), the typical time where $\mu g$ is achieved will depend on the time it can function or resist without consuming itself at reentry, which will be between 1 month to a couple of years. Construction, handling and lift-of costs are below 200 K USD in total (including the launch), which is much lower than any of the platforms mentioned above capable of generating $\mu g$ environments. Certain restrictions are present, mainly size (the Cubesat platform has less than 3000 cc in volume) and power consumption (less than 3 W), but these can be overcome by smart and low-cost setups.

A new setup to measure the injected power into a granular gas in $\mu g$ is already designed and in construction to be placed in the new, already approved SPEL missions. Following the work of Falcon et al., 1999, a small cylinder of 1 $\text{cm}^3$ will be filled with 100 grains of 300 μm, which are driven out of equilibrium by the action of a piston attached to a home-made oscillating solenoid. The impact of each grain will be measured by a MEMS nanoaccelerometer (LIS331HH from ST). The driving amplitude generation and the data acquisition will be performed by an Arduino. This simple setup can be easily exported to a Cubesat platform in order to measure collision rates and injected power in a $\mu g$ environment. For simple experiment suitable for Cubesats, the novelty of this work relates to the time offered for the experiments which is large and might be comparable only to that offered within the ISS. Although the experiment has to be less sophisticated due to the weight, volume and power constraints of Cubesats, the cost can be also much lower.

## 5. Magnetospheric/ionospheric research

Ionospheric instabilities and irregularities are manifestations of complicated phenomena that involve the Sun-Earth relationship. Although, space science has evolved greatly over the last several decades, the current state of understanding and forecasting is still limited. As our technological society grows increasingly connected and reliant on space-based communication and navigation systems, a growing number of users are susceptible to transionospheric signal degradation. Models of the Sun/Solar wind/Magnetosphere/Ionosphere interaction (Valdivia et al., 1996; Klimas et al., 1999; Vassiliadis et al., 2000; Stepanova et al., 2003; Diaz et al., 2010), needed to forecast and try to compensate degradation, rely on measurement capabilities that for different reasons are scarce. Current data sources divide into satellite-based measurements and ground-based measurements, with both types of measurements having advantages and disadvantages. Thus far, satellite measurements have been scarce due to the cost and technical limitations (energy, computational power, communication links, etc.) of satellite missions. On the other hand, ground-based measurements obtained using remote sensing techniques have less technical restrictions but are geographically limited (hard to place them over the oceans) and usually require significant assumptions in order to estimate physical parameters.

It is expected that physical models of the space environment will eventually allow prediction and quantification of the effects on Earth of phenomena triggered in space (space weather prediction). However, in a similar fashion to Earth climate models, space weather models must be fed with actual data in order to resolve ambiguities in the numerical solving process. While satellites and ground-based instruments have helped us explore space physics in our neighborhood they might be impractical in a sensor network configuration capable of continuously feeding global models. On the other hand, although Cubesats may have limitations, which impose hard constraints to instruments that can be used in them, they can offer the ability to monitor with improved temporal and spatial frequency at a lower cost.

Together with work on developing instruments that can probe the near space environment and yet can fit in Cubesats, it is relevant to study the possibilities of Cubesats that carry limited instruments, but in a larger number. Some of the manifestations that are possible to detect at low orbits, in the ionosphere, and even on ground are: waves, particle precipitation, electric field enhancements, magnetic field oscillations, currents, density disturbances and light generation (Aurora) (Valdivia et al., 1999; Stepanova et al., 2005). Some of these signatures are related to each other, and therefore estimation or measurement of a set of them might lead to estimation of the others. Additionally, the determination of these variables can also give insights about the physics that drives them.

Within SPEL, the focus is to use three type of instruments/techniques to be placed in Cubesats which can be combined with ground-based magnetometer networks and Incoherent Scatter Radars (ISRs). For the SUCHAI Cubesat, we carry a simple Langmuir probe as a proof of concept for combination of in situ measurements and ISRs. In the other two 3U Cubesats we plan to place Magnetometers, Langmuir Probes, double frequency GPS and/or communication radios (transceiver/receiver) for Total Electron Content (TEC) measurements.

### 5.1. Magnetic measurements

Magnetic fields are essential in characterizing different plasma regions in and around the Earth magnetosphere. Fluxgate magnetometers, such as those in the NASA led THEMIS mission (Auster et al., 2009) and similar to those used in the magnetometer array SAMBA, are the most common sensors to probe Earth's magnetic field in space (Acuna, 2002; Diaz et al., 2009). However, heritage fluxgates sensor designs are not optimized for deployment on ultra-small satellites, such as Cubesats and femto-satellites. On the other hand, Anisotropic MagnetoResistance (AMR) sensors have more favorable mass, volume and cost properties but the sensor intrinsic performance is not sufficient for many space science applications. Nevertheless, Brown et al. (2012) suggest that operating the sensor in a driven, first-order closed loop mode, significantly improves low field sensitivity and offset drift, and performance within an order of magnitude of a high end fluxgate has been achieved in a single-axis design. The developed magnetometer is inexpensive, simple to implement and sensitive enough for many scientific applications including detection of geomagnetic waves and structures. A three-axis design of this AMR is currently used in the TRIO-CINEMA Cubesat constellation mission. Besides the trends on magnetometer improvements in hardware, there are improvements based on algorithm and signal processing techniques to remove sources of magnetic contamination, with the technical approach based on sensing with an array of magnetometers and on-flight calibration procedures (Clavier et al., 2011).

A relevant ground-based (remote sensing) technique is based on the magnetometer arrays such as the African Meridian B-Field Education and Research (AMBER) and the South American Meridional B-field Array (SAMBA). In particular, SAMBA is located along Chile with stations from Putre (close to Arica city in the very North of Chile) to Antarctica. Since 2002 Chilean scientists, led by Dr. Stepanova, have been collaborating with the University of California Los Angeles and the Air Force Research Lab in the SAMBA international project financed by NSF and AFRL (P.I., E. Zesta). The magnetometer array and in particular SAMBA array can study multiple phenomena such as: (1) Equatorial density variation and the connection to the equatorial electrojet (Yizengaw et al., 2013), (2) The plasmasphere mass density distribution and its effect on radiation belt fluxes (Boudouridis and Zesta, 2007), (3) ULF wave propagation and magnetosphere-ionosphere coupling (Cuturrufo et al., 2015) and (4) Dynamics of auroral electrojects during strong geomagnetic storms (Vassiliadis et al., 2000). The magnetometers used by SAMBA are fluxgate magnetometers similar to those used in the NASA Time History of Events and Macroscale Interactions during Substorms (THEMIS) mission, which study aurora formation. Although THEMIS and SAMBA can combine data, a LEO tiny satellite array with magnetometers might improve the estimation process of SAMBA and give improved remote sensing information about the ionosphere. For instance, estimation of electron density can be achieved up to the interior of the magnetosphere by using magnetic field line oscillations in the Pc5 band. Subtracting the electron density content made with a LEO satellite from the measurement made with SAMBA the electron density content of the ionosphere can be estimated from the magnetometers.

#### 5.1.1. Magnetometers

Although there are different kinds of magnetometers such as SQUID (Super Conducting Quantum Interference) (Yang and Enpuku, 2003; Pizzella et al., 2001; Meyer et al., 2005), GMI (Giant Magneto Impedance), and Overhouser or Hall effect magnetometers (Moutoussamy et al., 2007; Duret et al., 1995), they are not the most relevant magnetometers for space applications, or are not even suitable for Cubesats in the short/medium term. The most relevant magnetic sensors considered for space-based science research are the search coil, fluxgate and magneto resistive magnetometers. In particular, the later technology appears

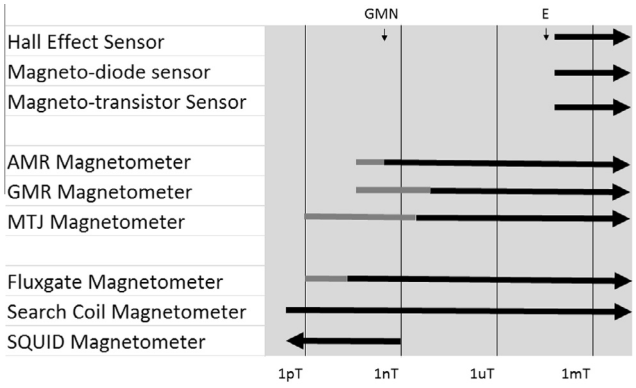

Fig. 2. GMN: Geomagnetic Noise. E: Earth's magnetic field.

more feasible for Cubesat projects. There are several reviews on different types of magnetometers and applications (Lenz and Edelstein, 2006; Caruso et al., 1998). Fig. 2 shows only a portion of magnetometers and sensors and their dynamic range.

Search coil and fluxgate magnetometers are similar vector magnetometers based on high magnetic permeability materials and two sets of large intertwined coils. The coils react to a change of magnetic flux given by Faraday's Law, reaction that can be measured (Roux et al., 2009; Coillot et al., 2007). The difference between both types lies in the fact that the sensor core of the fluxgate magnetometer is periodically saturated in both polarities (Burger, 1972; Ripka et al., 1995), increasing the reluctance measured and thus making difficult for the magnetic field to go through. Although the Search Coil is widely considered a large sensor, the ability for sensing weak magnetic field and the robustness are key elements, so that it is still used and active on space missions (Parrot et al., 2006). Even when current research shows a trend for miniaturization and low power, this type of magnetometer is still active (Parrot et al., 2006; Grosz et al., 2011). Nevertheless, the fluxgate magnetometer is one of the most used magnetometers for space research, since using the ring core geometry multiple axes measurements can be achieved with extreme simplicity, controlling frequency and feedback field (Acuna and Pellerin, 1969). Missions like the Pioneer 11 (Acuna, 1974), BepiColombo (Glassmeier et al., 2010) and DAWN (Magnes et al., 2003) have used fluxgate magnetometers. Commercial fluxgate magnetometers are available and they have been evaluated for space missions (Diaz et al., 2009; Matandirotya et al., 2013).

On the other hand, a less used but more suitable for nano-satellite missions is the magneto resistive magnetometer (MM), which is a device that changes its resistance ($\Delta R$) in the presence of an external magnetic field. This particular device is known for being very inexpensive and simply polarized. Although several kinds of this particular magnetometer exist (such as: AMR, GMR, MTJ, SDT, EMR, BMR, etc), the most relevant to Cubesat missions are the Giant Magneto Resistance (GMR) and the Anisotropic Magneto-Resistance (AMR). This magnetometer is usually a permalloy of Ni-Fe over a Si wafer, being composed of four of this permalloys arranged in a Wheatstone bridge (Hauser et al., 2003; Honywell, 2008). The response of this device is non-linear, but a particular technique is used for the linearization: barber poles, designed as conductive shunts formed by Au stripes. The stripes help with linearity by forcing the current inside to orient with a $45\,^{\circ}$ or $-45\,^{\circ}$ orientation with respect to the default magnetization (Endoh et al., 1988; Tumanski, 1984). (Incidentally this is the most linear point of a $cos^2\theta$ function, which is part of the model of the magnetometer). The different directions that the *barber-pale* takes generates a greater output, helping also with noise reduction. Tatiana-2 (Liu et al., 2012) and TRIO-CINEMA (Brown et al., 2012) are examples of missions that currently use AMR magnetometers.

The coming missions at SPEL (two 3U Cubesats) will include AMR magnetometers and are based on the topology developed for MAGIC (Magnetometer of Imperial College) (Brown et al., 2012; Brown et al., 2014) and used in the TRIO-CINEMA mission. The system will use a COTS AMR magnetometer provided by Honeywell, HMC1001. The HMC1001 was specially designed for low field magnetic sensing. Using the on-chip straps such as "Set/Reset" and "Offset", it is possible to create a negative feedback by turning the sensor in a null detector and to reduce the noise by changing the magnetization of the permalloy with periodic-bipolar electric pulses. The band that will be analyzed is very close to DC (0.1 Hz–10 Hz), which has a predominant flicker noise with a $1/f$ spectrum noise (Schmid, 2007). The HMC1001, among other COTS components, showed the lowest noise spectrum at the frequencies of interest (Stutzke et al., 2005), leading to the conclusion that this specific magnetometer may have an advantage in Cubesat missions. Regarding the price, in the history of space-based magnetometers, fluxgates were generally constructed considering all the requirements of that mission and for a unique design purpose and were usually custom made. This greatly increases price and fabrication time. The HMC1001 is a COTS chip that can be bought online and delivered in approximately 8 days with a reasonable price, a huge advantage considering the usual budget and development time of Cubesat missions. The HMC1001 has a size that is approximately of $10\text{ mm} \times 7\text{ mm}$ making it considerably smaller than a fluxgate. The particular MAGIC topology needs a periodic-bipolar current pulse of roughly 5A to work at the best operating point, which could have the penalty of a high power consumption. However, MAGIC demonstrated only a nominal consumption of approximately 400 mW in science mode. Different types of magnetometers may be able to reduce this value further (Acuna, 1974), but generally a space-based magnetometer using a fluxgate can use up to 2 W with the disadvantage of size. The power consumption is a relevant feature since resolution increases with it. The second magnetometer version at Imperial College used a 17 V rail (Brown et al., 2014) which might not be present in regular Cubesat systems, where 12 V is the largest spacecraft bus provided voltage value commercially available. Therefore, it is necessary to evaluate the impact on sensitivity that lower voltage rails (12 V, 5 V and 3.3 V) might have. In addition, there are mechanical and electrical challenges in order to implement a solution that goes from the boom deployment system to the processing electronics in order to satisfy the processing speed. Table 1 shows the specifications and values obtained by Imperial College (Brown et al., 2012; Brown et al., 2014), which are expected to be achieved and improved by our group work for operation within 3U Cubesats or less.

Considering all the specifications given in Table 1, some of them are previously considered targets, such as the volume and mass. On the other hand, improvements can be made on terms of noise density by using low noise

Table 1
Instrument specifications.

| | |
|---|---|
| Mass | 104 g (total) |
| Volume | Sensor head 10 $cm^3$<br>Electronics 173 $cm^3$ |
| Dynamic range | ±57,500 nT |
| −3 dB point | 16 Hz |
| Noise density | 150 pT $Hz^{-1/2}$ above 1 Hz |
| Operational temperature | −50 °C to +60 °C (electronics)<br>−120 °C to +80 °C (sensor) |
| Flipping frequency | 512 Hz |
| Sensitivity | 2 nT |
| Vectors | 32 |
| Decimation | 324 |
| Bus rails | 17 V, 5 V, 3.3 V (no 17 V will be present on this mission) |
| Power | 425 mWHz |

electronics. For example, MAGIC used OP484 as their primary amplification device, which is a general purpose amplifier. This device has an offset of voltage of 65 μV and 3.9 $nV/\sqrt{Hz}$ of noise density at 1 kHz. Other devices can be found with better performance, such as ISL28134 with just 2.5 μV of offset voltage, or the OPAx228 with just $3nV\sqrt{Hz}$ and very similar offset voltage. A trade off can be balanced in this case, with more stable and passive offset compensation to achieve better noise performance, as a means of comparison to determine which figure might be a more significant influence on the precision and performance of the sensor. All of this can be accomplished using only COTS components.

### 5.2. Ionospheric measurements

Another ground-based technique, one of the most relevant to estimate ionospheric plasma parameters when plasma is in thermal equilibrium (Diaz et al., 2010), is the so called Incoherent Scatter Radar (ISR) (Evans, 1969; Sheffield, 1975; Bauer, 1975; Walker, 1979; Holt et al., 1992). In this technique, a powerful radar is used to remotely probe the ionosphere. The majority of the backscattered power from the ionosphere is confined within a narrow (typically tens of kHz at UHF center frequencies) double humped band centered close by to the transmitted frequency. This is referred to as the ion line, or ion spectrum, and its shape is described by ionospheric parameters such as electron to ion temperature ratios, ion drift velocities, and electron density, ion composition, among others (Zettergren et al., 2011). A second mode, more difficult to detect but still accessible to ISRs, is the Langmuir mode, which is manifest in narrow bands offset from the carrier by the mean plasma frequency of the backscatter volume. Although much weaker in general, this feature has also been used to derive parameters of the ionospheric plasma, such as the plasma critical frequency (Showen, 1979), the density of suprathermal electrons (Nilsson et al., 1997), the ambient electron temperature (Nicolls et al., 2006), and indirect information on the distribution of velocities of photoelectrons (Farley, 1970).

Some ionospheric plasma parameters can be measured directly, such as the ion acoustic speed variation that is inferred from the spectrum Doppler shift. But most relevant state parameters are derived from the ion line through inversion techniques (Lehtinen and Huuskonen, 1996). Other ionospheric parameters such as the wind speed and the temperature of the neutral atmosphere, or the static electric field strength, are subsequently calculated once the state parameters are determined (Beynon and Williams, 1978). Plasma state parameters can be obtained from the analysis of the incoherent scatter spectrum or from its Fourier transform, the auto-correlation function (ACF) of the scattered signal (Folkestad et al., 1983). Individual ACFs are usually obtained from lagged products of samples of the scattered signal for each ionospheric range (Wannberg et al., 2010), although some authors sum and store all the lagged products to analyze ACFs as a whole profile (Grydeland et al., 2004). This multi-parameter fitting is a complex procedure, often having no unambiguous solution. Variation of different plasma parameters lead to similar changes in the theoretical spectrum (Vallinkoski, 1988), making the resulting plasma parameters non-unique particularly if more than one ion species is present (Vallinkoski, 1988). A solution often implemented to solve this problem is to record raw signals, allowing the possibility of applying different off-line methods of analysis (Potekhin et al., 2008). Studies and analyzes related to the fitting process, or inversion process for plasma parameter estimation began in 1960s and have evolved from a table of possible cases to more automated optimized models where the error of the process can be also estimated (Ho and Moorcroft, 1971; Swartz, 1978; Holt et al., 1992; Cabrit and Kofman, 1997; Nikoukar et al., 2008; Shcherbakov et al., 2009; Bauer et al., 2013). The core of the current implemented algorithms in most ISRs around world are based on a Bayesian approach, which implements a non-linear least-squares fitting process that uses the Levenberg–Marquardt algorithm. The results for the temperature ratio obtained with this methodology of fitting in the ACF has been confirmed by comparison with other procedures such as the Langmuir plasma line and power from the ion line spectrum (Wand, 1970).

Currently the most extended software packages to analyze ISR's data include the Optimal Analysis of Signals from Incoherent Scatter (OASIS) (Holt et al., 1992; Cabrit et al., 1996) and the Grand Unified Incoherent Scatter Design and Analysis Program (GUISDAP) (Lehtinen, 1986; Lehtinen and Huuskonen, 1996; Wannberg et al., 1997; Damtie, 2004; Li et al., 2012). Other studies use different off-line algorithms to perform the inversion procedure with different benefits. A trust-region approach (Coleman and Li, 1996) is implemented in Milla et al. (2013) giving more robustness than the Levenberg–Marquardt algorithm, and also allows for lower and upper bounds to the solution. A lag–profile inversion procedure based on a statistical inversion is used in Virtanen (2009) giving a direct applicable solution to raw voltage data from radar transmissions that are arbitrarily modulated. The analysis is still under development for more recent IS facilities which have implemented their own software to analyze the data (Domnin et al., 2014; Bogomaz and Kotov, 2014). However, the fusion of multiple data (a sensor network approach) is the main motivation of our group and we plan to revisit the estimation procedure with more modern techniques such as Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 1995). PSO provides a more computationally efficient method and would allow the use of values to constrain the estimation procedure with a simpler implementation.

### 5.2.1. Langmuir probes

Langmuir probes (Mott-Smith and Langmuir, 1926) have been widely used to determine plasma electron density and temperature in space as well as in the laboratory (Bekkeng et al., 2010). The Langmuir probe works by placing an exposed conductor in a plasma, biasing it relative to a reference potential and measuring the collected current. A swept bias probe sweeps the bias voltage from a negative to a positive value. The shape of the current response characteristic makes it possible to determine electron density, electron temperature, and the spacecraft potential. Many comparisons between ISRs and Langmuir probes were done in the early days of Incoherent Scatter studies using rocket-borne probes (Walker et al., 1968) and ionosondes (Vanzandt and Bowles, 1960) to verify the parameters obtained with radars. Initial large discrepancies were found on the comparatives mainly because of the quality of the measurement probes and the radar height resolution in upper ionosferic regions. Early satellite comparisons were also affected by the Langmuir probes' quality and impurity effects, but advances in material composition of the probes reduced the differences (Benson et al., 1977; Schunk and Nagy, 1978). Most of the discrepancies were also related to the non-simultaneous measurement of all variables at the same radar beam location. The first satellite that provided an on-board propulsion system capable of maintaining a desired low-altitude orbital track over a station for a period of time was the Atmosphere Explorer-C satellite (Benson et al., 1977). More recent satellite deployments have compared ion temperature with ionospheric models, and indicate that models are still not able to forecast some effects of the ionosphere (Chao et al., 2006). Regardless of technical advances, the sweep time (typically 1 s (Lebreton et al., 2006)) of a Langmuir probe makes it unsuited for determining small-scale density structures on a rocket or satellite. Accordingly, newer concept Langmuir probe systems have been developed by Jacobsen et al. (2010), reporting the possibility of deriving the electron density with high time resolution without the need to know the electron temperature and the exact value of the plasma potential. The technology uses a probe biased at a positive value well above the estimated plasma potential. The developed system consists of four needle probes and a data acquisition unit. This Langmuir probe system was verified both in a plasma chamber and on board the ICI-2 sounding rocket launched from Svalbard on December 2008. Post-flight analysis of the data generated by the instrument on the ICI-2 rocket flight has been done, verifying that the instrument worked as intended, and the probe was able to resolve electron density structures down to sub-meter scales. A miniaturized low-power system is under development in order to be used on board CubeSTAR, a 2U Cubesat from the University of Oslo. The SPEL is working on a design that would follow this philosophy, although in the first mission, the SUCHAI, a classical spherical Langmuir probe was used based on Dr. Hank Voss' design (Voss et al., 1998).

Although, the current state of Langmuir probes suitable for a Cubesat platform have some limitations, a valid research question is related to the amount of information that this limited instrument might add to the estimation procedure of other instruments, in particular ISRs, ground-based magnetometer and GPS networks. For instance, ISRs then use the total cross section measured by the radar to estimate electron density and then subsequently constrain the inversion procedure to estimate other plasma parameters from the ion acoustic ACF or spectrum. Electron density obtained from total power of the echo has uncertainty and error, but offers valuable information to the estimation procedure of the other plasma parameters. In that sense, electron density and even electron temperature obtained with current Langmuir probes might offer valuable information to the estimation procedure of ISRs. If the performance (sensitivity, precision, resolution dynamic range, etc.) of current technology Langmuir probes does not provide enough information to improve ISR estimation procedures, it would be valuable to estimate the necessary Langmuir technology improvements that have to be achieved. In addition to the theoretical work we are performing, it is necessary to obtain data from combined experiments between Langmuir probes and ISRs. The missions discussed in this article are planned in part to provide the preliminary data about this research question.

## 5.3. Radio beacon and ground-based receiver instrument for TEC measurements

A radio beacon consists of a transmitter of coherent radio waves of two different frequencies in the VHF and UHF bands. These radio signals will propagate through the ionosphere if the transceiver is placed in a satellite, from the satellite in space, orbiting above the region of maximum plasma density, to a ground-based receiver. By measuring the phase difference of the received radio waves at different frequencies, it is possible to obtain measurements of total electron content (TEC) along the path between the satellite and the ground station (Davies, 1990; Bernhardt and Siefring, 2006). Radio beacon instruments have been widely used onboard Low Earth Orbit satellites such as OSCAR, Cosmos, DMSP F15, COSMIC and C/NOFS. Recently, the Coherent Electromagnetic Radio Tomography (CERTO) instrument onboard satellite was used to obtain TEC measurements at the low latitudes (de La Beaujardière et al., 2004; Hei et al., 2014). Currently, this type of space instrument has not been installed in Cubesats mainly due to restrictions of space, energy and weight. By developing radio beacons that can satisfy the technical requirements of nanosatellites, it will be possible to develop new missions for obtaining TEC measurements in the ionosphere.

New developments in software-defined radio allow for the use of digital receivers to detect signals from satellites (Yamamoto, 2008). Following a similar approach, we propose to develop receivers using software-defined radio equipment. This methodology offers significant advantages due to the high degree of flexibility, reduced cost and development time. The transionospheric radio signals will be acquired by the receivers in order to measure the phase difference and digital signal processing will be applied to the measurements in order to obtain the TEC.

At least one of the upcoming 3U Cubesats, under development at SPEL-Universidad de Chile will carry a radio beacon in order to perform TEC studies. The design, development and construction of the nano-satellite radio beacon and ground-based station that will receive the transmitted signals will be conducted in collaboration with the Jicamarca Radio Observatory (JRO) - Instituto Geofisico del Peru (IGP). The JRO goal in developing this instrumentation is to contribute to the advancement of the study of ionospheric physics by building radio beacons that can be utilized on Low Earth Orbit nano-satellites or even on constellations of these spacecrafts. In addition to nano-satellite instrument development, a ground-based receiver will be built to acquire the signals emitted by the nano-satellite radio beacon. This common objective between JRO and SPEL provides a great opportunity for international collaboration. In that sense, this mission could motivate even more multinational collaborations in Latin America in the field.

This space instrumentation will be used to research the ionospheric variability and phenomena that occur in low latitude regions. In particular, it would allow us to obtain TEC maps and detect plasma irregularities responsible for radio scintillations by measuring variations in the total electron content. By increasing the number of ground-based receivers, tomography techniques can be applied to these TEC measurements in order to derive the plasma density as a function of geographic position and altitude (Austen et al., 1988). Observational studies will help in our understanding the temporal and spatial evolution of plasma irregularities at low latitudes by combining the obtained TEC with radar measurements such as Jicamarca radar data. Furthermore, the results obtained will add valuable information to the ionospheric ground-based instruments due to the global coverage of a satellite. It is of high scientific interest to measure TEC in adjacent regions near these ground-based instruments to study the latitudinal and longitudinal variations of plasma density in the ionosphere. On the other hand, the Universidad de Santiago de Chile in collaboration with the Universidad de Chile (through SPEL) will install a GPS PolarRx PRO receiver (supporting GPS/GLONASS/GALILEO/BEIDOU) in the frame of an American-Chilean AFORS grant. The GPS receiver will be placed in Putre (north of Chile) during 2015, which will allow us to collaborate on TEC measurements from the ground with JRO. In addition, the Universidad de Chile new Cubesats will carry two frequency GPS receiver which can also be used for TEC measurements Heine et al., 2015. In fact, the GPS systems perform automatic calculation of TEC for positioning correction. The TEC based on GPS data is expected to serve as comparison to the radio beacon technique, together with the possible analysis of data fusion, to improve estimation and models.

## 6. Conclusion

We have presented and dicussed the SUCHAI project grounds and scientific motivations. The desired following steps and the designed path were also discussed in this article. We presented, to the best of our knowledge, a summary of the current efforts made for different groups around the world to increase the performance of instruments for space research, such as Langmuir probes, magnetometers, TEC systems and microgravity/hard environment platforms. All of these approaches can be used within Cubesats. We plan to follow some of these approaches in order to improve instrument capabilities. However, our main goal as a group is to study the potentialities that Cubesats can offer using current state of the art instruments (with the current limitations). Studies to sustain and manage a Cubesat constellation were discussed, mostly from the point of view of (1) digital fabrication for fast development and (2) prognostic/health management in particular for batteries. These techniques however might be extended in the future to other critical components or subsystems. In addition, within the SPEL (and collaborating institutions) we will carry out studies in quantification, from the point of view of added information (information theory), of the benefits multiple in situ values might have in the estimation procedures of ground based instruments such as Incoherent Scatter Radars, magnetometers, and GPS networks.

In any case, the most important lesson thus far from this Chilean case/experience is that the new Cubesat standard has been capable of facilitating the long desired satellite-based research within the Chilean space community. Our space program was started from scratch in just 4 years. Of even greater benefit, the possibilities that this platform offers of distributing the cost and risks of a mission, together with facilitating collaboration between specialized groups in different system, subsystems and payloads/experiments (e.g. JRO-UCH-USACH collaboration) offers many opportunities to pursue space research in Chile and Latin America. These approaches were unthinkable 5 years ago. Many Latin America countries have already launched Cubesats or have the capabilities to do so. With this article, we hope to bring international attention to space research conducted by the Cubesat community in Latin America. An attractive set of experiments exists that we can perform with current Cubesat technology, in such a manner that highlights the potential of Latin America contributions to the exploration and monitoring of space.

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