13.er Premio Durán Farell de Investigación Tecnológica

Candidatura Projecte:

FSSCat: the 1st CubeSat-based ESA Third Party Mission contributing to the Copernicus program to Monitor Essential Climate Variables of the Water Cycle

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1. PROJECT SUMMARY

The FSSCat is ESA's first mission that relies on CubeSats to support the Copernicus monitoring services for the land and marine environments of the European Earth Observation program. The mission won the Sentinel Small Satellite (S^3) Challenge Award of ESA and was honored as the Copernicus Masters Overall Winner in 2017.
On September 3rd, 2020, the European Space Agency (ESA) launched the FSSCat mission into space using a VEGA SSMS. Students and young researchers at the UPC NanoSat Lab of the Universitat Politècnica de Catalunya- BarcelonaTech (UPC) used proprietary technology onboard two 6-unit CubeSat-type nanosatellites to generate the first maps of soil moisture; sea ice concentration, extent and thickness; and Arctic salinity. The shoebox-sized nanosatellites, called ^{3}Cat-5/A and ^{3}Cat-5/B, have provided the data to the land and marine environment Copernicus services. According to Copernicus policy, the data are open and available from the European platform NextGEOSS, which is a federated data hub for access and exploitation of Earth observation data.

Academic research

The mission was successfully conducted at UPC facilities. First, the UPC NanoSat Lab, a laboratory for the design and manufacture of payloads and small satellites. It is located in the UPC's North Diagonal Campus, and linked to the Barcelona School of Telecommunications Engineering (ETSETB), the CommSensLab-UPC research center of the Department of Signal Theory. Second, the Montsec satellite ground station (SGSMontsec), in Lleida, which has been receiving the scientific data from the mission. The station was developed *ad hoc* by the UPC NanoSat Lab and is managed jointly with the Institute of Space Studies of Catalonia (IEEC).
UPC doctoral degree holders *Joan Francesc Muñoz* and *Joan Adrià Ruiz de Azúa* have developed the microwave payloads and the SGSMontsec together with doctoral students *Lara Fernandez* and *Adrián Pérez*, from the UPC's Department of Signal Theory and Communications.
Additionally, doctoral students *David Llaveria* and *Christoph Herbert*, and doctoral degree holder *Miriam Pablos*, former graduate from CommSensLab-UPC, currently working at the Institute of Marine Sciences of the Spanish National Research Council (CSIC), have actively collaborated in the processing of data. The group has been led by UPC NanoSat Lab director *Prof. Adriano Camps*.
The main objective of the mission was to monitor polar ice and soil moisture while testing inter-satellite communication systems in order to create a future network of federated satellites. Such satellites are devised to share on-board sensors, loads and systems to perform certain operations, like downloading data, collaboratively. The satellites of the mission have used optical and radio links to test advanced concepts of federated satellites and other ground sensors.

Novel miniature technology for Earth Observation

The students and young doctoral degree holders at the UPC NanoSat Lab designed two payloads that have flown aboard the ^{3}Cat-5/A: 1) an UHF inter-satellite link, and 2) the Flexible Microwave Payload-2 (FMPL-2) a dual instrument combining an L-band microwave radiometer with radio frequency interference detection and mitigation capabilities, and a global navigation satellite system reflectometer (GNSS-R) using GPS and Galileo signals.
The GNSS reflectometer acts as a radar, but without sending any signals, just receiving the direct signals from other navigation satellites, and the same signals reflected from the Earth's surface. In addition to providing altimetry data, the spread of the signal in the time delay and Doppler coordinates allows to obtain information about the reflecting surface, such as sea ice or open ocean, or surface soil moisture over land.
This dual microwave system (FMPL-2), which weighs only 1 kg and fits inside a module of less than 1 liter of volume, has provided Earth observation data with a spatial resolution of about 600 m at 500 km height with the GNSS-R, and about 350 x 500 km with the L-band radiometer.
The novelty of the mission lies on the new or improved scientific quality geophysical products resulting from the combination of these two sensors plus the visible and near-infrared optical imagery, which are all obtained from satellites the size of a shoebox (CubeSats).

The data from the L-band microwave radiometer have been processed similarly to those of ESA's SMOS mission, launched in 2009 in collaboration with the Institute of Marine Sciences. While the SMOS mission data are used to provide disaggregated moisture maps at 1 km resolution by merging with visible spectrum and near infrared data, the FSSCat, although based on a much poorer native resolution, provides disaggregated products at 36 km.

In fact, the ³Cat-5/A and ³Cat-5/B nanosatellites have provided data on essential climate variables to monitor with highly accurate spatial and temporal resolutions at a fraction of the costs associated with conventional satellites. The data confirm, for example, that the year 2020's minimum Arctic ice extent was the second lowest in the satellite record. Funded and supervised by ESA, the final FSSCat mission has been carried out by a consortium that is made up of the UPC's NanoSat Lab, DEIMOS Engenharia (the Portuguese branch of the Elecnor Deimos group), Golbriak Space OÜ (Estonia), Cosine Remote Sensing (the Netherlands) and Tyvak International (Italy), which was responsible for testing the platforms, integrating components and performing operations during the mission.

The ɸ-sat-1 technology demonstrator was also on board, it is ESA's first artificial intelligence in space and it has filtered out images of the Earth that were not suitable for use because of cloud cover.

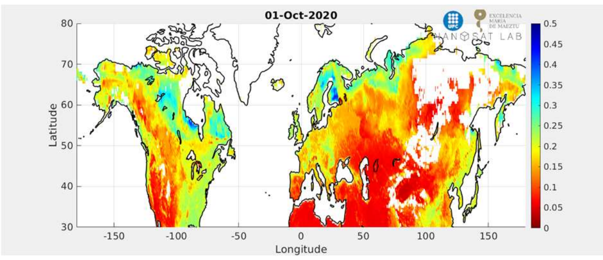
Technology transfer and Economic Impact

Following UPC NanoSatLab specifications, the FMPL-2 radio-frequency front-ends have been designed and manufactured by Balamis SL, an UPC spin-off company co-founded by Prof. Camps.

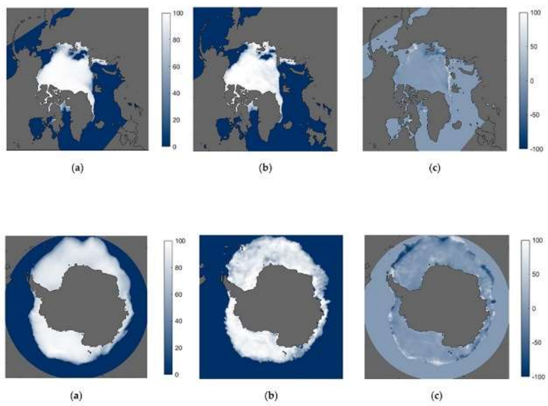
The algorithms and data processing algorithms developed in FSSCat have been transferred to Deimos Eng. and will be the core of the data processing ground segment proposal for the **Atlantic Constellation**, a constellation of 16 small satellites, 8 from Portugal, and 8 from Spain, carrying GNSS-R payloads similar to the FMPL-2 ones. The Atlantic Constellation will be funded by the recently approved Aerospace PERTE (see support letter from Miguel Bello, to be appointed as commissioner for the Aerospace PERTE by the Council of Ministers).

Societal Impact

Obtaining data and understanding the behavior of soil moisture and sea ice extent and thickness **is essential to understand the water cycle, since the behavior of ocean water, clouds and ice determines the planet's climate and causes several atmospheric phenomena**. The movement of water masses, or thermohaline circulation, transports energy in the form of heat and mass in the form of dissolved solids and gases around the globe, reducing differences. This circulation makes the heat go from the warmest to the coldest areas and vice versa; it acts as a giant radiator. Several elements are involved in this process, such as temperature, salinity and soil moisture, which are related to atmospheric phenomena like El Niño, major floods or droughts. **These phenomena influence both populations and several economic sectors in many different ways: affecting crops or creating possibilities of new sea routes through the Arctic**.



Top image: animation of one of the maps showing the soil moisture evolution, also in non-frozen areas, from October 1 to December 4.



Maps of Arctic (top) and Antarctic (bottom) sea ice concentration from 13 to 15 November 2020: (a) map with FMLP-2 microwave radiometer, (b) ground truth map, and (c) error map.

2. PROJECT DESCRIPTION

2.1. Introduction

A quick historical review of UPC NanoSatLab Activities

The activities of what it is today the UPC NanoSat Lab started in 2007 after UPC Chancellor, Prof. Antoni Giró, tasked Professors Juan Ramos and Adriano Camps the development of two tractor projects: one in the field of "aeronautics," and another one in the field of "space" to aggregate the efforts and know-how of several UPC engineering schools, and notably the Aeronautics schools that had been recently created in Terrassa and Castelldefels. Unfortunately, no specific budget was allocated for these tasks, and despite applying to numerous calls, the activities had to be conducted in a best effort basis "in the cracks" of the usual projects (time and budget wise), and supported by project remnants to feed these "new space" activities[1].

The first project was the UPCSat-1, renamed later as ^{3}Cat-1 (pronounced /Cube-Cat One/), a 1 unit (1U) CubeSat including a number of technology demonstrators coming mostly from the Department of Signal Theory and Communications, and the Department of Electronics Engineering, the two that at that time had more background on space-related activities. The project started as a mix of subsystems that were purchased, those that we considered critical such as the On-Board Computer (OBC), the Electrical Power System (EPS), the structure itself etc. and subsystems developed in-house. However, it was soon realized that neither the CubeSat "standard" was a complete standard (as it only defined the mechanical requirements, but not electrical ones, so there were incompatibilities in the connectivity of some of the subsystems purchased), nor some of the subsystems purchased really deserved the name of space qualified (e.g. EPS with some components not really ready for space, or others with serious design "issues" etc.).

In these circumstances, it was decided to step back and start designing the different subsystems inhouse, as the only way to make sure that we knew what was inside… It was somehow a sort of "vertical integration," because of the severe budget constraints. In our way to try to use commercial off-the-shelf (COTS) components, and we, little by little, started creating what is now called the UPC NanoSat Lab, and in the office space we occupied in 2007 in the Omega-3 building of UPC Campus Nord, we started bringing in a customized Thermal Vacuum Chamber (TVAC) for the bake-out and thermal cycling tests, a Sun simulator with a COTS Xenon lamp with an spectra cross-checked against an Oriel Top of the Atmosphere Sun simulator.

In 2013 we received co-financing to purchase a long-waited electro-dynamic shaker to conduct all the vibration tests. Because of the special requirements (too heavy) the UPC NanoSat Lab was migrated to a basement between the A3 and B3 buildings at UPC Campus Nord.

In May 2018, thanks to a "María de Maeztu" grant awarded to the CommSensLab Research Center (Dept. of Signal Theory and Communications) an ISO 8 clean room was going to be installed. At that time, we were kindly "invited" to move, and thanks to the school of Telecommunications Engineering (ETSETB-UPC) dean, Prof. Ferran Marqués, and UPC Chancellor, Prof. Francesc Torres, a new location was provided in the basement of the C4 building, in the same UPC Campus Nord. Today's UPC NanoSat Lab was inaugurated on November 2018 [1]. At the time of writing this candidacy, we have just received from AST Science a bigger shaker as a donation, that will be installed in a small room next to the current facilities. This will allow the lab to grow, and also offer a better service to national and international companies, as the original facilities were dimensioned according to the needs of a University lab, with a quite limited budget.

However, the growth of the UPC NanoSat Lab cannot be completely explained without an academic perspective. To put things in the historical context, in March 2010, on the occasion of the 10th anniversary of the Bologna Process, the European Higher Education Area (EHEA) was launched. As the main objective of the Bologna Process since its inception in 1999, the EHEA was meant to ensure more comparable, compatible and coherent higher education systems in Europe. It implies the establishment of new teaching methodologies, to the detriment of traditional master classes: Continuous Assessment, and Practical Teaching. After having compared several models for the definition of the new curricula, the ETSETB-UPC identified the Conceive-Design-Implement-Operate (CDIO) initiative as the most complete and coherent model. In the new curricula, the CDIO initiative is implemented with four subjects: Introduction to Information and Communication Technologies (ICT) engineering (or ENTIC), Basic Engineering Project (or PBE), Advanced Engineering Project (or PAE, the capstone project), and the Final Degree Project. Prof. Camps was among the core team of faculty that worked on the implementation of the CDIO initiative at the ETSETB, and since its inception, a PAE subject called under the generic term "^{3}Cat-NXT" was offered to the students willing to learn more about space activities, electronic design,

[1] Note that the term "New Space" was coined just in 2004, but it has only gained acceptance in the past 10-15 years.

programming, testing etc. [2]. The course starts with an intense 11 h tutorial on different aspects related to spacecraft systems engineering that levels the different student backgrounds, depending on their majors, and provides some basic understanding on the main design considerations that apply to spaceborne systems, that do not apply for -for example- consumer electronics. The topics change every semester according to the UPC NanoSat Lab's main activities and projects, but typically they are connected along 3-4 semesters. This creates a bit of extra overhead to the students, because of the extra work to document and report for the next semester students, but also helps them to understand how a real project in a company is, including internal reporting to a team leader, weekly oral presentations and progress meetings with the faculty, taking minutes of the meeting (MoM), with action items, as well as three main project meetings including Preliminary and Critical Design Review meetings, and Final Review meeting.

Since the ³Cat-NXT PAE subject started, we estimated that about 300 students have followed this course, and many of them have continued space-related activities in the lab during their Final Degree project, and some of them in their Master's Thesis, or even Ph.D. Thesis. And more interestingly, the lab is not restricted to students from the ETSETB-UPC, students from other UPC Schools, and from different Spanish Universities, and also from different countries have been welcome to join an international multi-disciplinary, and "multi-generation" (from freshmen to post-docs) working environment.

In the next sections, the UPC NanoSat Lab facilities, and main missions will be explained.

UPC NanoSat Lab Facilities

The facilities of the NanoSat Lab are designed to carry out the assembly, integration and test procedures of up to 6U CubeSat spacecrafts and subsystems. An ISO 8 cleanroom area that includes all the necessary instrumentation and testing equipment to perform verification and validation procedures (Fig. 1).

Fig. 1. UPC NanoSat Lab clean room with TVAC and shaker

- *Thermal Vacuum Chamber*

A custom made cylindrical Thermal and Vacuum Chamber (TVAC) that emulates the outer space conditions is also available. It is mainly used for the environmental test campaigns in CubeSat missions. It has a heating system based on three infrared lamps and a cooling system based on liquid nitrogen that circulates around the thermal shroud. Internal temperature can be controlled from -196 ºC to +300 ºC, while the minimum pressure is 10^{-5} mbar. This allows to simulate the pressure and thermal cycles of a satellite in orbit. The facility is operated by a centralized computer that controls the temperature and vacuum levels depending on a target reference. 2.92 mm (K-type) RF connectors, DB-9, and thermo-couples are available at the feedthroughs. The Device Under Test (DUT) can be hanged from the top of the TVAC or placed on a plate thermally insulted from the shroud, which can rotate thanks to a magnetically coupled motor. The TVAC also features a large quartz window to allow the light from a Sun simulator to illuminate the DUT, and a Germanium lens to observe the temperature distribution in the DUT.

- *Shake table*

Vibration tests in all three axes can be sequentially carried out in the electrodynamic shake table model Data Physics GW-V400 [3]. Sine (frequency sweep), random, and some shock tests can be conducted.

- *Helmholtz Coils and air bearing*

The Helmholtz Coil System is a set of three pairs of coils manufactured by Serviciencia SL, that generate an arbitrary magnetic field which is uniform in a cubic of ~40 cm side. The system includes an air-bearing to test attitude determination and control systems (ADCS) in near zero-g conditions. The current that flows through the coils is generated by a triple power supply controlled by a computer, and it can mimic the Earth's magnetic field while the satellite is orbiting around the Earth (Fig. 2).

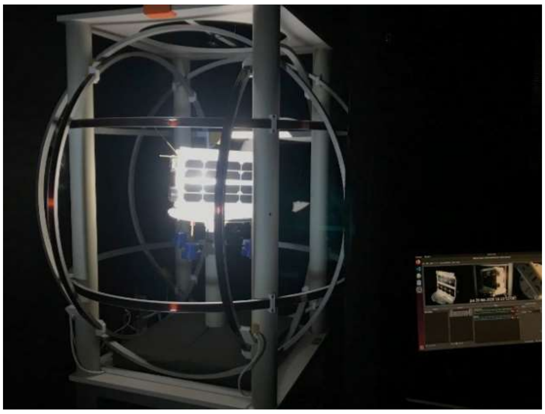


Fig. 2. Helmholtz coils during ADCS testing of a 6U CubeSat (picture courtesy of NanoAvionics)

- *Ground Station*

The UPC NanoSat Lab also designed, manufactured, and operates its own ground station (Fig. 3). It includes quadantennas at Very High Frequency (VHF) from 144 to 145 MHz; Ultra High Frequency (UHF) from 435 to 438 MHz; and a 3-m dish at S-Band from 2200 to 2290 MHz. It si located at the Observatori Astronòmic del Montsec (OAdM) premises, which is owned and operated by the Institute of Space Studies of Catalonia (IEEC). VHF and UHF are transmit/receive, and exhibit a G/T of -16 and -14 dB, respectively. S-band is receive-only, and exhibits a G/T of + 9 dB.

Fig. 3. IPC ground station at IEEC Observatori del Montsec Premises.

UPC NanoSat Lab Main Projects

In this section, the main satellite missions developed by the lab are explained.

- *^{3}Cat-1*

^{3}Cat-1 (Intl. designator 2018-096K) was the first project of the lab: a 1U educational and techdemo mission [4]. It was started in 2007, and it was ready for launch in 2014, but the first Russian invasion of Ukraine prevented it from being launched using a Dnepr rocket. After this failed attempt, it was re-scheduled for a launch in a Falcon 9, but for two occasions the previous launch exploded (June 2015 and September 2016). It was finally launched from Sriharikota Launching Range (India) using a PSLV in November 2018.

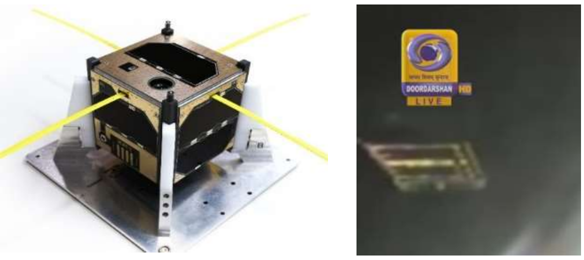


Fig. 4. ^{3}Cat-1 (left), and moment in which it was injected in orbit (right)

^{3}Cat-1 included the following payloads: 1) an "eternal" self-powered beacon using a Peltier cell to generate electricity thanks to the temperature gradient between the inner and outer parts of the satellite, 2) a CellSat photovoltaic solar cell developed by the Micro- and Nano-Technologies group from the Electronics Engineering Dept at UPC, 3) a monoatomic oxygen detector based on the analysis of the resonant frequency of a MEMS device covered by a sensible polymer, 4) an experiment to characterize a Graphene Field Effect Transistor (GFET), 5) an experiment to test the effects of plasma in Wireless Power Transfer (WPT) links, 6) a VGA-resolution CMOS camera, and 7) a Geiger counter.

- *^{3}Cat-2*

^{3}Cat-2 (Intl. designator 2016-051B) was a 6U Earth Observation mission [5]. It was launched from Jiuquan Satellite Launch Center using a Long March D2, in August 2016. ^{3}Cat-2 payload was PYCARO, a dual-frequency (L1 and L2), dual-polarization (RHCP and LHCP), and dual-constellation (GPS and Galileo) Global Navigation Satellite Systems-Reflectometer (GNSS-R).

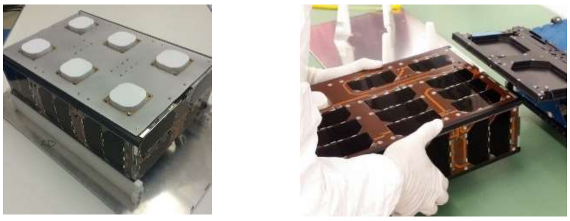


Fig. 5. ^{3}Cat-2 nadir looking antenna array (left), and ^{3}Cat-2 during integration in the DuoPack deployer at ISIS premises.

- *^{3}Cat-3*

Leveraging on the ^{3}Cat-2 experience, ^{3}Cat-3 was meant to be a multi-spectral imaging mission for the Cartographic and Geologic Institute of Catalonia (ICGC) [6]. Unfortunately, despite being included in its Strategic Plan, political issues at Catalan and Spanish levels prevented it from being approved, and the mission stopped after a Phase A study. This mission is reincarnated as GenEO, also called "Menut", the second mission of the New Space strategy of the Catalan government after "Enxaneta".

- *^{3}Cat-4*

^{3}Cat-4 mission aims at demonstrating the capabilities of smallest nano-satellites for Earth

Observation (EO), in particular using GNSS-R and L-band microwave radiometry, as well as for Automatic Identification Services (AIS) [7]. The goals of this mission are mainly educational, technology demonstrator of the Flexible Microwave Payload-1 (FMPL-1) which implements the three RF payloads in a single software defined radio, and scientific, including dual-frequency (L1 and L2) GNSS-R and assessing the required ionospheric corrections, and the creation of RFI maps.

^{3}Cat-4 was selected by the European Space Agency (ESA) Academy for the "Fly Your Satellite!" program (second edition). Its launch is foreseen for Q4 2022 in the maiden flight of Ariane 6. Fig. 6 shows an artist's view of the satellite with the ~50 cm antenna deployed.

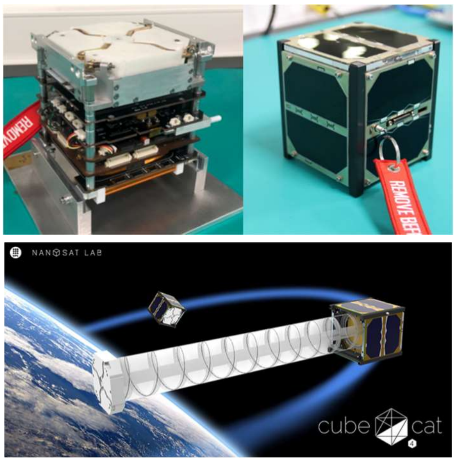


Fig. 6. ^{3}Cat-4 nadir looking antenna in stowed configuration (top left), fully integrated (top right), and artists' view.

- *FSSCat: ^{3}Cat-5/A and ^{3}Cat-5/B*

^{3}Cat-5/A and ^{3}Cat-5/B (Intl. designators 2020-061W and 2020-061X) were the two 6U CubeSats forming the FSSCat mission. The "Federated Satellite Systems/^{3}Cat-5" (FSSCat) mission was the winner of the 2017 ESA S^3 (Sentinel Small Satellite) Challenge and overall winner of the Copernicus Masters competition. FSSCat was launched from Kourou Space Port (Guiana Space Centre) using the VEGA 16 SSMS PoC on September 3rd, 2020.

The primary goals were the generation of coarse resolution soil moisture, sea ice extent and thickness maps using L-band microwave radiometry and GNSS-Reflectometry, enhanced resolution soil moisture maps applying pixel downscaling techniques, and the test of techniques for future satellite federations. Secondary goals were sea surface salinity and wind speed maps. ^{3}Cat-5/A carried UPC's Flexible Microwave Payload–2 (FMPL-2), a software defined radio payload implementing an L-band microwave radiometer and a GNSS-Reflectometer [8]. ^{3}Cat-5/B carried Cosine's HyperScout-2 visible and near infrared + thermal infrared hyperspectral imager [9], enhanced with the PhiSat-1 board, an onboard Artificial intelligence experiment for cloud detection [10]. Both CubeSats include an optical inter-satellite link from Gölbriak Space, and a UHF inter-satellite link tech-demos from UPC to test the concept of satellite federations. FSSCat scientific results can be seen in [11].

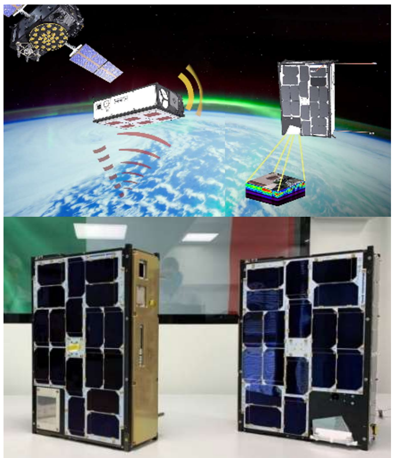


Fig. 7. (top) ^{3}Cat-5/A left and ^{3}Cat-5/B right: FSSCat mission concept, and (bottom) spacecrafts (courtesy of Tyvak).

- *^{3}Cat-6*

^{3}Cat-6/FMPL-3 is an L5/E5a GNSS-R reflectometer hosted payload onboard the GNSS augmentation Signaling (GNSSaS) mission a 6U CubeSat from NSSTC/UAEU (Fig. 8, [12]). It also includes VHF and UHF receivers for ionospheric scintillation studies. It was shipped on October 2020 to UAE, and it is waiting for final integration and launch in Q2 2023.

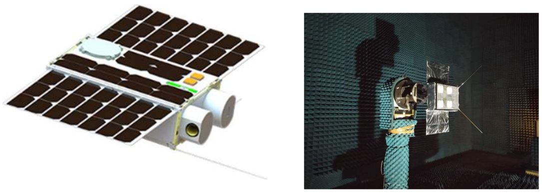


Fig. 7. GNSSaS satellite, and ^{3}Cat-6/FMPL-3 2x2 L5/E5a antenna array for GNSS-R.

- *^{3}Cat-7*

^{3}Cat-7/RITA is a combined hyperspectral imager, L-band microwave radiometer, and LoRa IoT communications Techdemo hosted payload onboard the AlainSat-1 mission, a 3U CubeSat from NSSTC/UAEU, and one of the winners of the 2^{nd} IEEE GRSS Student Grand Challenge (Fig. 9). It will be shipped to UAE in summer 2022, and launch in expected for Q2 2023.

Fig. 8. AlainSat-1 artist's view (left) and flight model of the ^{3}Cat-7/RITA payload.

- *^{3}Cat-8*

^{3}Cat-8 is the newest UPC NanoSat Lab project. It is a 6U CubeSat ionospheric research mission featuring a number of novel technology demonstrators: a deployable Fresnel Zone Plate antenna for GNSS-Radio Occultations to analyze ionospheric scintillation, a polarimetric multi-spectral camera to study ionospheric emission, an electrospray ionic motor (courtesy if Ienai SL), a SOS radio beacon (courtesy of C3S), an in-house designed PocketQube deployer (see next section), and an autonomous beacon for improved satellite identification.

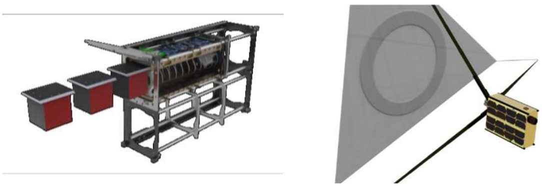


Fig. 9. Artists views of ^{3}Cat-8 Cupid PocketQube Deployer (left), and with the Fresnel Zone Plate antenna deployed (right).

^{3}Cat-8 was also the winner of the Allén Space contest[2] and it will board the Allén Space's new Triskel on-board data handling system.

- *^{Po}Cat's*

The UPC NanoSat Lab is also developing an "Open PocketQube Kit" for the Institute of Electrical and Electronic Engineers (IEEE). These PocketQubes, generically named "^{Po}Cat's" (pronounced /PoCat/), will be delivered by the end of 2022, together with all designs and oftware as an educational tool and to lower the entry barrier of new actors in the space. The payloads of the three PocketQubes are: a VGA camera, an L-band and a 24.25-25.25 GHz RFI monitoring receivers. Two replicas of these ^{Po}Cat's will be deployed from ^{3}Cat-8 and will be used to test Satellite Federation Concepts among them, the mother satellite (^{3}Cat-8), and ground.

This brief historical review has presented the UPC NanoSat Lab, its facilities, and the main projects conducted over the past 15 years, which have been developed without a specific institutional support, but with the remnants of other projects, except for FSSCat and the ^{Po}Cat's, These projects have been conducted by more than 300 students that have followed the Advanced Engineering Course at the ETSETB curricula linked to the UPC NanoSat Lab, while many others from several degrees have developed their Bachelor or Master's final degree project in the lab. Prof. Camps and a team of graduate students were at the heart of the writing of the Catalan New Space Strategy [13].

[2] https://alen.space/triskel-mission-award/

2.2. FSSCat Project Objectives

In the following Sections the **FSSCat project** will be explained. The "Federated Satellite Systems" (FSSCat) mission was the **winner of the 2017 ESA S^3 (Sentinel Small Satellite) Challenge** and the **overall winner of the 2017 Copernicus Masters competition**.

The project was **conducted** in a record time **from May 2018 until 2021**.

FSSCat consists of two 6-unit CubeSats. The mission **primary goals** are the generation of:

1) coarse resolution soil moisture, sea ice extent and thickness maps using L-band microwave radiometry and GNSS-Reflectometry,

2) enhanced resolution soil moisture maps applying pixel downscaling techniques by combining passive microwave and multi-spectral optical data, and

3) the test of techniques for future satellite federations.

Secondary goals are:

4) the generation of sea surface salinity and wind speed maps.

FSSCat has been the first ESA Third Party mission based on CubeSats.

2.3. Relevance of the work

Technical relevance

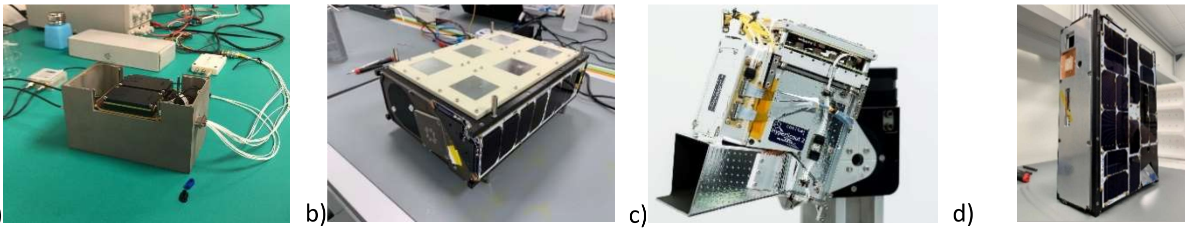
- **^{3}Cat-5/A** (International designator 2020-061W) carries the Flexible Microwave Payload–2 (FMPL-2) [1] designed and implemented by the Universitat Politècnica de Catalunya (UPC). **FMPL-2** inherits the concept of the PAU instrument, which combines an L-band microwave radiometer and a GNSS-Reflectometer in a single instrument [2]. It is the **first instrument of its type, and the first GNSS-R and first L-band microwave radiometer onboard a CubeSat**. Both instruments are implemented using a Zynq-7000 [14]. A custom-made RF-Front End from Balamis SL[3] includes the low noise amplification, filtering, and frequency conversion stages, as well as a hot load, and an active cold load for calibration purposes. Figure 11 shows the FMPL-2 block diagram.

- **^{3}Cat-5/B** (International designator 2020-061X) carries the HyperScout 2 hyperspectral imager with a field of view is 31°×16° field of view [3]. HyperScout 2 includes two channels: channel 1 in the visible and near infrared, with 4000×1850 pixels, and 45 bands from 400 to 1000 nm, with a spectral resolution of 16 nm; and channel 2 in the thermal infrared, with 1024×768 pixels and 3 bands from 8 to 14 μm, with spectral resolutions of 1100 nm in the first two bands, and 6000 nm in the third one. **HyperScout 2** has augmented processing performance by using the PhiSat-1 board featuring the Myriad 2, the **first artificial intelligence chip ever in a satellite**, which improves the data processing capabilities for hyperspectral imagery [4].

- Additionally, both CubeSats include an optical inter-satellite link from Gölbriak Space, and a UHF inter-satellite link tech-demos from UPC to test novel concepts of satellite federations.

The implementation of this challenging mission in just 1.5 years would not have been possible without the participation of Deimos Engenharia (PT), administrative prime contractor of the mission and responsible for the Data Processing Ground Segment, Tyvak International (IT), platform provider, system integrator, CubeSat deployer and launch interface provider, and operations manager, and ESA EOP which initiated the ESA Sentinel Small Satellite Challenge, provided technical and programmatic advise and expertise, the funding scheme, and access to ESA testing facilities.

[3] Balamis SL is a UPC spain-off company co-founded by Prof. Camps. Its CEO is Dr. Roger Jové, a PhD student of Prof. Camps, responsable for the ^{3}Cat-1 mission.



a) b) c) d)

Fig. 10. a) FMPL-2 combined microwave radiometer and GNSS-reflectometer, b) 3Cat-5/A and dual-band nadir looking antenna, c) HyperScout-2, and d) 3Cat-5/B with HyperScout-2 baffle on the bottom right corner.

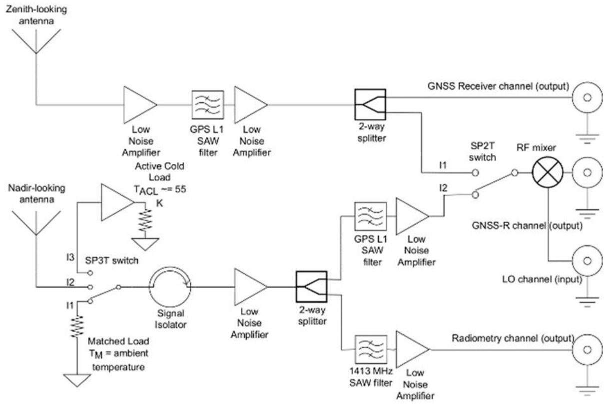


Fig. 11. FMPL-2 payload RF front-end. First connector on the right-hand side goes to a navigation receiver, the second one is an input of a Software Defined Radio (Rx #1), the third one is a transmitter channel (Tx #1) used as local oscillator, and the fourth one is the second input of the Software Defined Radio (Rx #2) (adapted from [14]).

Scientific relevance

The **rationale to combine both sensor technologies for the very first time** is the following, and the results obtained illustrate their combined power:

- On one side, **L-band microwave radiometry** can be used to infer surface soil moisture and sea ice thickness up to ~60 cm [16]. Downscaled soil moisture maps can be generated using validated algorithms developed for ESA SMOS using VNIR data [17]. An integration time of 100 ms was selected for the microwave radiometer, as the radiometric sensitivity is enough to compensate for the wind speed effects of the brightness temperatures over the ocean.
- On the other side, **GNSS-Reflectometry** can be seen as a multi-static radar with as many transmitters as visible navigation satellites, and it can be processed as a scatterometer, an altimeter, or as an unfocused synthetic aperture radar. The most general GNSS-R observable is the so-called Delay-Doppler Map (DDM), which (in conventional GNSS-R) is computed as the cross-correlation of the reflected signal with a locally-generated replica of the transmitted one for different Doppler frequencies and delay bins [18]. GNSS-R is very sensitive to the surface where the scattering is taking place. The peak and shape of the DDM contain information on the reflectivity, and mean squared slopes of the surface where the scattering is taking place. Over the ocean the DDM is much more spread in both the delay and Doppler frequency domains than it is over sea ice or land [19], and this spread can be related to the wind speed.

To optimize the spatial resolution for sea ice extent detection, the GNSS-R incoherent integration time was set to 40 ms, so that the blurring induced by the subsatellite point movement equals the size of the first Fresnel zone.

FMPL-2 was executed over the poles following a 5-day basis: 5 days in a row over the North Pole at latitudes >55°, and 5 days in a row over the South Pole at latitudes <-55º. The minimum latitude was decreased to 45° after ~1 month of the mission, and finally to 35°, thanks to a positive power budget and the downlink capacity of ^{3}Cat-5/A data at the UPC ground station at the Observatori Astronòmic del Montsec (OAdM), owned and operated by the IEEC [20].

Five scientific products have been obtained using Artificial Neural Networks (ANN) that have been trained using different input variables for each product, and "ground truth" as the output.

Soil Moisture

Soil Moisture (SM) is obtained using a 2-hidden layer feed-forward ANN with 7 neurons in each. The input variables are the land surface temperature (ECMWF ERA 5 skin temperature, at 30 km resolution), multispectral images (notably the red and near infra-red channels, or the NDVI from NASA MODIS, at 1 km spatial resolution[4]), and the FMPL-2 L-band brightness temperatures at right hand circular polarization (nadir-looking antenna with 350 km x 500 km footprint). The ANN is trained with 60% of the data to avoid overfitting, using the 36 km SMAP soil moisture product, and the training is interrupted after 20 epochs.

Figure 12a shows a sample soil moisture map produced over a week. Figure 3b shows the scatter plot of the soil SMAP moisture values and the FMPL-2/ANN retrieved ones. The R^2 coefficient is 0.8, and the standard deviation of the error wrt. the SMAP product is 9.2%. The interested reader is referred to [21] for further details.

Sea Ice Concentration and Extent

Sea ice concentration (SIC) maps are generated using L-band microwave radiometry and GNSS-R data. Two regression fit ANNs are used for each data with 3 hidden layers of 5, 10 and 5 neurons each, and 5 and 8 input variables, respectively. For L-band microwave radiometry it has been trained using OSI SAF [22] or NSIDC ground truth as a target output, and the FMPL-2 brightness temperature, its along-track standard deviation and gradient, the ECMWF ERA 5 skin temperature, and the land cover fraction (%) are used as input variables. For GNSS-R the inputs are the FMPL-2 brightness temperature, the averaged DDM, the reflectivity, the standard deviation of the reflectivity, the DDM SNR, the elevation angle of the reflected signal, the land cover fraction within an area larger than the antenna half-power footprint, the ERA 5 skin temperature. It is worth noting that all variables were bilinearly interpolated to the GNSS-R specular reflection points, and that the FMPL-2 brightness temperature was needed to improve the performance of the network. Both networks were trained using ~15.000 random samples for each pole, and validated using ~5.000 random samples for each pole.

Sea Ice Extent (SIE) maps are generated using a binary classification ANN with a single hidden layer with 10 neurons. Figure 4 shows sample SIE (top) and SIC (bottom) maps for the Arctic and Antarctica, as derived from FMPL-2, and the performance of these ANNs is summarized in Table 1. As it can be appreciated in Figs. 13a and 13b, although the GNSS-R reflectivity is only available over the specular reflection points, its variations offer a finer granularity of the sea ice extent that is not captured by the microwave radiometry data. The interested reader is referred to [23] for further details.

Sea Ice Thickness

Sea Ice Thickness (SIT) maps are generated using a predictive regression model - Deep Neural Network (DNN) with one normalization layer, two hidden dense non-linear layers (64 neurons), and one linear single-output layer. The input variables are the FMPL-2 microwave radiometer data, the ECMWF ERA 5 skin temperature, and the OSI SAF OSI-401-b SIC product.

a)

b)

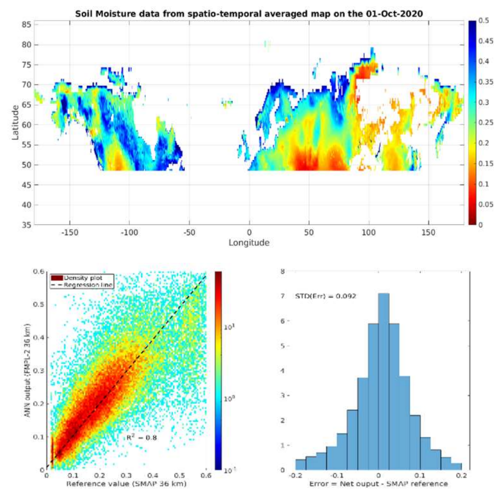


Fig. 12. a) Weekly average soil moisture map derived from FMPL-2 using an ANN, and b) error statistics (from [21]).

[4] Note: HyperScout-2 data was not available at the time of processing the FMPL-2 data, so MODIS data was used instead.

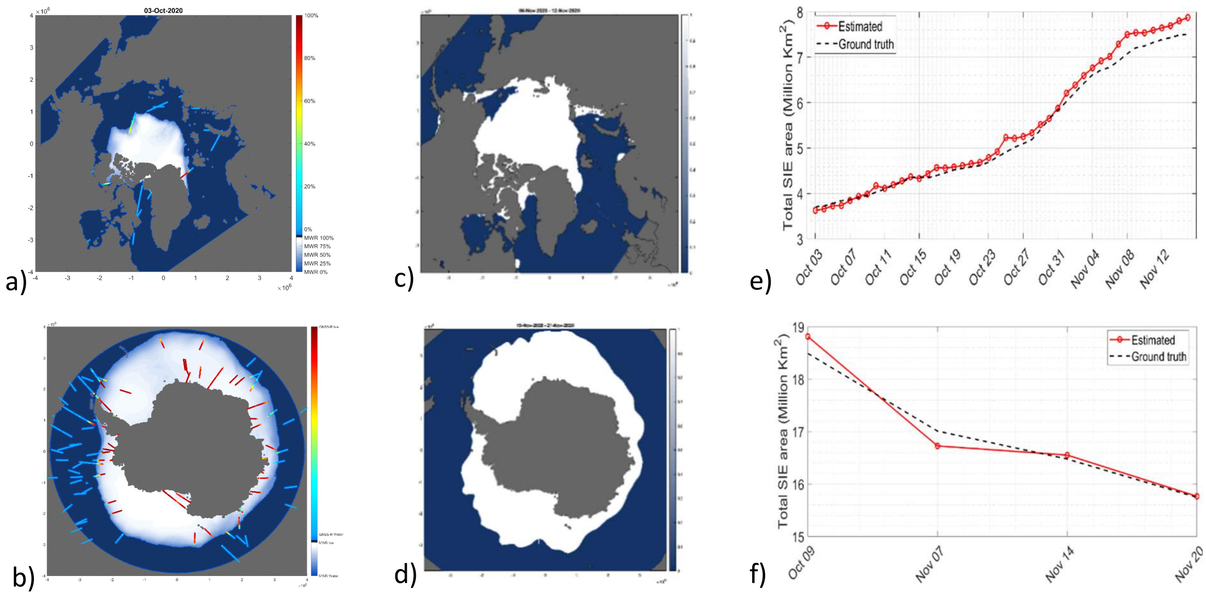


Fig. 13. Sample SIE (top) and SIC (center) maps for the Arctic and Antarctica, as derived from FMPL-2, and temporal evolution during October and November. Error is < 6% when compared to OSI SAF "ground truth" (adapted from [12])

Table 1. Summary of the performance of the sea ice concentration (SIC) and extent (SIE) ANNs.

Errors wrt to OSI SAF products.		**Arctic**		**Antarctic**	
		SIC	SIE	SIC	SIE
MWR error	Global	2.37%	1.95%	5.55%	3.57%
	Ice areas (SIC > 90%)	2.87%	0.02%	5.25%	0.21%
	Water areas (SIC = 0%)	1.05%	1.52%	2.35%	2.90%
	Transition areas (0 < SIC < 90%)	11.27%	8.50%	11.30%	7.33%
GNSS-R error		2.80%	1.10%	2.29%	1.00%

The "ground truth" used as training output variable is the daily Sea-Ice Thickness product from SMOS. Figure 14 presents some results for the a) Arctic, and b) Antarctica, as well as the associated error metrics: c) the scatter plot of the SMOS-derived SIT used as a ground truth and the FMPL-2/DNN-predicted SIT showing a good agreement up to ~50 cm SIT, and d) the Mean Absolute Error (MAE) histogram, showing a nearly unbiased SIT prediction with a standard deviation of 6.5 cm. The interested reader is referred to [24] for further details.

Sea Surface Salinity

Sea Surface Salinity (SSS) maps are generated using an ANN topology with two hidden layers and 8 neurons per layer. SSS can be derived from L-band microwave radiometry data, but the SSS signature is easily hidden by the sea surface roughness effects. The best SSS results are achieved when using L-band radiometry data, Sea Surface Temperature (SST) data set, and GNSS-R data (reflectivity, and standard deviation of the reflectivity computed in a moving window) together with the elevation angle of the reflected signal as a proxy for sea surface roughness. The ANN is trained using 20% of the available points. Figure 15 shows sample results of the SSS retrieved, ground truth, and error maps over a) the Arctic, b) Antarctica, and error statistics: c) SMOS SSS ground truth/FMPL-2 ANN SSS scatter plot, and d) MAE histogram.

As a matter of fact, using similar ANNs the 10 m height wind speed can also be estimated with a correlation coefficient of 0.89, and a rmse of 1.68 m/s. The interested reader is referred to [25] for further details.

FSSCat is the first ESA Third Party Mission based on CubeSats[5], and data is freely available at: https://catalogue.nextgeoss.eu/

In a nutshell, **the scientific relevance of the FFSCat mission can be summarized as follows**: *"by* ***combining*** *for the* ***very first time L-band microwave radiometry data, GNSS-R data****, and* ***hyperspectral*** *data acquired* ***from CubeSats*** *(FMPL-2 onboard* [3]*Cat-5/A, and HyperScout-2 onboard* [3]*Cat-5/B), it is possible to* ***derive*** *a number of* ***essential climate variables*** *(ECVs) associated to the* ***water cycle*** *with* ***scientific quality****, namely surface soil moisture, downscaled using VNIR data, sea ice concentration, extent and thickness, and sea salinity. Wind speed results have also been obtained, as a proxy to retrieve the sea surface salinity."*

FSSCat has also shown the **potential of small satellites to conduct valuable science missions, as gap-fillers between high-end missions, to reduce the revisit time, or as part of constellations/networks of intelligent and interconnected Earth Observation satellites** providing **global near real-time data for digital twins of the Earth.**

Economic relevance:

FSSCat, as the winner of the 2017 ESA Sentinel Small Satellite and 2017 overall winner of the Copernicus masters competition, the "Oscars of Space", has demonstrated the capabilities of Catalan science and technology to develop microwave payloads and scientific missions. It can be said, that this has been a **key element in convincing the Catalan government to push the New Space Strategic Plan**[6], to which the members of the UPC NanoSatLab have contributed very significantly. Also, the same Department of Polítiques Digitals lists FSSCat as one of the key projects of this strategy.

[5]https://earth.esa.int/eogateway/news/introducing-the-newest-esa-third-party-missions
[6]https://politiquesdigitals.gencat.cat/ca/tic/estrategia-new-space-de-catalunya/

FSSCat was the key enabling technology used in the COPRIME ESA Scout Mission proposal. Unfortunately, this proposal was not selected, but the concept of combining an L-band microwave radiometry and GNSS-R payload (FMPL-2) and hyperspectral imagers as in FSSCat is the payload choice of the **Atlantic constellation** that will be formed by **8 satellites from Spain, and 8 satellites from Portugal**, and that will be developed under the **PERTE Aerospacial**[7] **(ACT 7)** presented by the Spanish government on April 4th, 2022.
The appendix includes a **support letter** to this candidacy from **Mr. Miguel Belló**, former CEO of the Deimos Group, current CEO of Air Center, and upcoming manager of the PERTE Aerospacial[8].

Social relevance:

"Global climate change has already had observable effects on the environment. Glaciers have shrunk, ice on rivers and lakes is breaking up earlier, plant and animal ranges have shifted and trees are flowering sooner. **Effects** that scientists had predicted in the past would result **from global climate change are now occurring**: loss of sea ice, accelerated sea level rise and longer, more intense heat waves."[9]
These effects are amplified in the polar regions, and therefore it is extremely important to register and monitor variations in the snow and ice extent and thickness, as they have a major environmental and economic impact around the world, such as temperatures increase, which will foster t**ropical disease propagation** (e.g. malaria, dengue…) to mid latitudes, respiratory issues…, changes in precipitation patterns, more often and more severe **droughts** and **heat waves** will impact **food production**, and stronger and more intense **hurricanes**, and **sea level rise** by up to ~2 m by 2100 **will affect the ~40% of the world population living in coastal areas**.

[7]https://www.ciencia.gob.es/dam/jcr:4cac69ae-6fc1-480a-af3d-f109d6664f1f/PERTE_Aeroespacial_Presentacion.pdf
[8]https://www.lamoncloa.gob.es/lang/en/presidente/news/Paginas/2022/20220609_aerospace-perte.aspx
[9]https://climate.nasa.gov/effects/

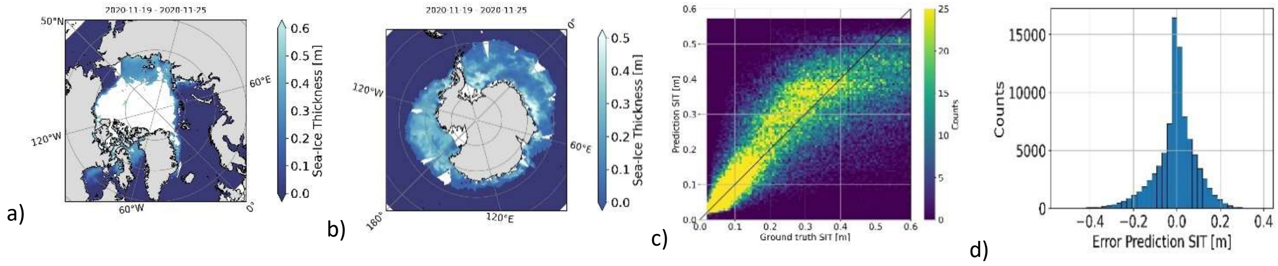


Fig. 14. Sample SIT maps over a) the Arctic, b) Antarctica, and error statistics: c) SMOS SIT ground truth/FMPL-2 DNN SIT scatter plot, and d) MAE histogram (from [12]).

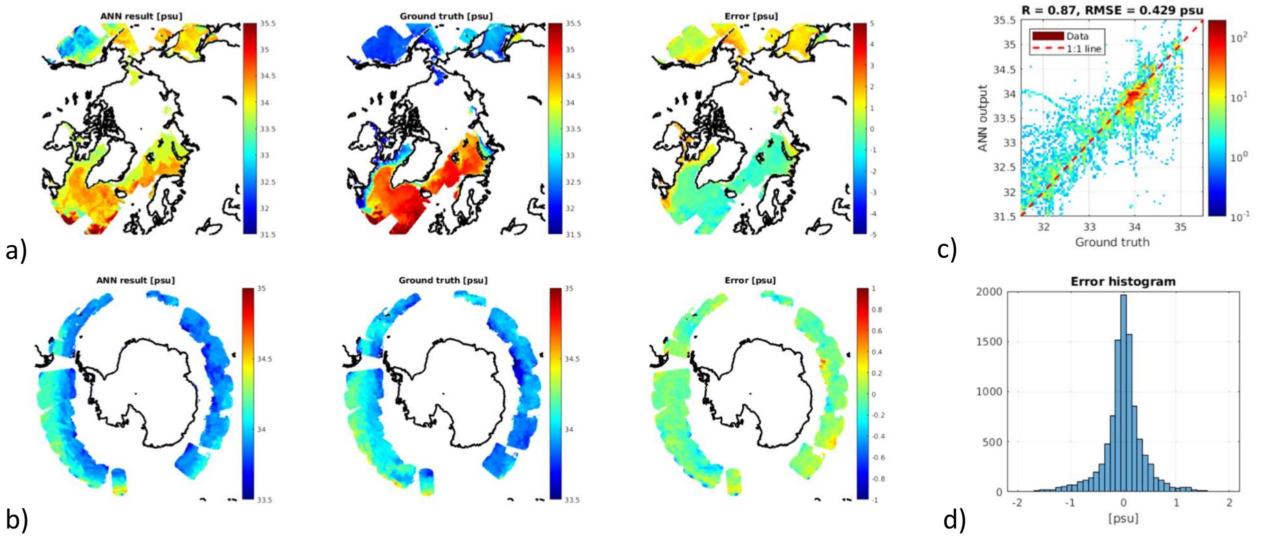


Fig. 15. Sample retrieved, ground truth, and SSS error maps over a) the Arctic, b) Antarctica, and error statistics: c) SMOS SSS ground truth/FMPL-2 ANN SSS scatter plot, and d) MAE histogram (from [25])

References

[1] https://nanosatlab.upc.edu/en

[2] http://www.cdio.org/files/document/file/design_of_the_advanced_engineering_project_subject_for_the_third_year_of_electrical_engineering_at_telecom_bcn.pdf

[3] https://www.dataphysics.com/shakers-and-accessories-literature/

[4] https://www.tandfonline.com/doi/full/10.1080/22797254.2017.1274568

[5] https://ieeexplore.ieee.org/document/7500113

[6] https://doi.org/10.3390/s18010140

[7] https://ieeexplore.ieee.org/document/8519037

[8] https://ieeexplore.ieee.org/document/9044708

[9] https://www.cosine.nl/cases/hyperscout-2/

[10] https://ieeexplore.ieee.org/document/9600851

[11] https://www.upc.edu/ca/sala-de-premsa/noticies/nanosat-lab-genera-per-primer-cop-des-de-cube-sat-mapes-gel-mari-i-humitat-terreny

[12] https://nsstc.ae/new/satellites/gnssas-satellite-1030

[13] https://politiquesdigitals.gencat.cat/ca/tic/estrategia-new-space-de-catalunya/

[14] J. F. Munoz-Martin, L. F. Capon, J. A. Ruiz-de-Azua and A. Camps, "The Flexible Microwave Payload-2: A SDR-Based GNSS-Reflectometer and L-Band Radiometer for CubeSats," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 13, pp. 1298-1311, 2020, doi: 10.1109/JSTARS.2020.2977959.

[15] A. Camps, X. Bosch-Lluis, I. Ramos-Perez, J. F. Marchan-Hernandez, B. Izquierdo and N. Rodriguez-Alvarez, "New Instrument Concepts for Ocean Sensing: Analysis of the PAU-Radiometer," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 10, pp. 3180-3192, Oct. 2007, doi: 10.1109/TGRS.2007.894925.

[16] HyperScout-2: https://www.cosine.nl/cases/hyperscout-2/ (last visited, December 31st, 2020)

[17] G. Giuffrida et al., "The Φ-Sat-1 mission: the first on-board deep neural network demonstrator for satellite earth observation," in IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2021.3125567.

[18] L. Kaleschke, et al., “SMOS sea ice product: operational application and validation in the Barents Sea marginal ice zone”. Remote Sensing of Environment 180. (2016): S. 264-273.

[19] G. Portal et al., "A Spatially Consistent Downscaling Approach for SMOS Using an Adaptive Moving Window," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 11, no. 6, pp. 1883-1894, June 2018, doi: 10.1109/JSTARS.2018.2832447.

[20]V. U. Zavorotny, S. Gleason, E. Cardellach and A. Camps, "Tutorial on Remote Sensing Using GNSS Bistatic Radar of Opportunity," in IEEE Geoscience and Remote Sensing Magazine, vol. 2, no. 4, pp. 8-45, Dec. 2014, doi: 10.1109/MGRS.2014.2374220.
[21]A. Alonso-Arroyo, V. U. Zavorotny and A. Camps, "Sea Ice Detection Using U.K. TDS-1 GNSS-R Data," IEEE Transactions on Geoscience and Remote Sensing, vol. 55, no. 9, pp. 4989-5001, Sept. 2017
[22]UPC NanoSatLab web site: https://nanosatlab.upc.edu/en/facilities-folder/ground-segment (last visited, March 25th, 2022)
[23]J.F. Munoz-Martin, D. Llaveria, C. Herbert, M. Pablos, H. Park, A. Camps, "Soil Moisture Estimation Synergy Using GNSS-R and L-Band Microwave Radiometry Data from FSSCat/FMPL-2." *Remote Sens.* **2021**, *13*, 994. https://doi.org/10.3390/rs13050994
[24]OSI SAF Sea Ice Concentration (SSMIS): https://osi-saf.eumetsat.int/ (last visited, January 9th, 2021)
[25] D. Llaveria, J.F. Munoz-Martin, C. Herbert, M. Pablos, H. Park, A. Camps, "Sea Ice Concentration and Sea Ice Extent Mapping with L-Band Microwave Radiometry and GNSS-R Data from the FFSCat Mission Using Neural Networks." *Remote Sens.* 2021, *13*, 1139. https://doi.org/10.3390/rs13061139
[26]C. Herbert, J.F. Munoz-Martin, D. Llaveria, M. Pablos, A. Camps, "Sea Ice Thickness Estimation Based on Regression Neural Networks Using L-Band Microwave Radiometry Data from the FSSCat Mission." *Remote Sens.* 2021, *13*, 1366. https://doi.org/10.3390/rs13071366
[27]J.F. Munoz-Martin, A. Camps, "Sea Surface Salinity and Wind Speed Retrievals Using GNSS-R and L-Band Microwave Radiometry Data from FMPL-2 Onboard the FSSCat Mission." *Remote Sens.* **2021**, *13*, 3224. https://doi.org/10.3390/rs13163224

2.4. Original scientific and technical contributions

The original scientific and technical contributions from the UPC NanoSatLab to the FSSCat mission are:

Technical:

- Novel satellite payload (FMPL-2) combining into a single instrument and L-band radiometer and a GNSS-Reflectometer.
- First time ever either an L-band radiometer or a GNSS-Reflectometer have been miniaturized to fit in a shoebox size satellite (6U CubeSat).
- Novel UHF inter-satellite links to test concepts on Federated Satellite Systems (the "Uber" of space).

Scientific:

- Development of novel algorithms (using Neural Networks, and fusing data from different sensors: L-band Microwave Radiometry, GNSS-Reflectometry data and multispectral visible/near-infrared optical imagery) to retrieve five Essential Climate Variables (ECVs) related to the Water Cycle with scientific quality: soil moisture, sea ice extension, concentration and thickness, and sea salinity.

2.5. Main Result

New concept payload fully developed at UPC NanoSatLab by graduate students obtains five ECVs (soil moisture, sea ice extension, concentration and thickness, and sea salinity) with scientific quality and demonstrates the **capability of small satellites to improve the revisit time or as gap fillers between "traditional" large satellite missions**.

2.6. Short and Mid Term Impact

The short and mid term impacts have already been discussed in Section 2.3, and it is worth separating them in economic and societal impacts.

Economic

The Aerospace PERTE recently approved by the Spanish government includes the development of the so-called **Atlantic Constellation** formed by 16 small satellites: 8 from Portugal, and 8 from Spain. The 8 satellites from Spain will include an **FMPL-2 type of payload with GNSS-R capabilities**. UPC has been contacted by one of the companies that will bid for it to provide these instruments. The Spanish part of the constellation will be managed by ESA through and open ITT (but restricted to Spanish companies) to be published early 2023.

In the mid-term it is expected that FMPL-2 type payloads small in volume and with low-power consumption be boarded in more satellites as hosted payloads. Actually, the evolved version of FMPL-2, FMPL-3 is already being integrated in the

GNSSaS satellite[10], from the UAE Space Agency, and it will be launched in Q2 2023. More international collaborations are being explored.

Societal

The societal impact goes beyond the creation of skilled jobs thanks to initiatives such as the Atlantic Constellation. Climate change and global warming are affecting society in many different aspects, from the preservation of ecosystems and biodiversity, to human health (e.g., more favorable propagation of disease vectors, more often and intense heat waves…), damages in infrastructure and transportation systems, as well as energy, food security, and water resources.

FMPL-2/FSSCat type of measurements, implemented in the Atlantic Constellation or in any other platform, will definitely contribute to a better understanding of the above problems by improving the measurement capability of essential climate variables, such as, over the ocean: sea level, surface winds and currents, sea state, sea ice extension, concentration and thickness cover, sea salinity, etc. and over land: soil moisture, above ground biomass, etc. with improved quality and better spatio-temporal sampling.

2.7. Patents and licenses derived from the work

Although implemented in a record time of 1.5 years, this has only been possible thanks to a long and sustained research which lead to 4 patents[11], some of which were already transferred to BALAMIS SL[12].

The algorithms developed have been transferred, as per ESA requirement of the ESA S^3 Challenge, to Deimos Eng. to implement the Data Processing Ground Segment in NextGEOSS.

2.8. Funding Sources

This work was supported by:

- 2017 ESA S3 challenge and Copernicus Masters overall winner award[13] ("FSSCat" project)
- ESA project "FSSCat Validation Experiment in MOSAIC"[14] (ESA CN 4000128320/19/NL/FF/ab),
- Spanish Ministry of Science, Innovation and Universities, "Sensing with Pioneering Opportunistic Techniques" SPOT, grant RTI2018-099008-BC21/AEI/10.13039/501100011033,
- Unidad de Excelencia Maria de Maeztu MDM-2016-0600,

And the following Ph D Felloships:

- Joan Francesc Munoz-Martin received support in the form of a grant for the recruitment of early-stage research staff FI-DGR 2018 from the AGAUR—Generalitat de Catalunya (FEDER), Spain
- Joan Adrià Ruíz de Azúa received support in the form of a grant for the recruitment of early-stage research staff FI-DGR 2018 from the AGAUR—Generalitat de Catalunya (FEDER), Spain
- Lara Fernández Capón received support in the form of a grant for the recruitment of early-stage research staff FI-DGR 2019 from the AGAUR—Generalitat de Catalunya (FEDER), Spain
- Adrián Pérez-Portero received support in the form of a grant for the recruitment of early-stage research staff FI-DGR 2020 from the AGAUR—Generalitat de Catalunya (FEDER), Spain
- David Llaveria received support in the form of a grant for the recruitment of FPU-2019 from the Ministerio de Universidades (FEDER), Spain
- Christoph Herbert received support in the form of an INPHINIT grant by La Caixa Foundation (Spain) in 2018.

[10] https://www.upc.edu/en/press-room/news/the-upc-has-developed-a-payload-for-a-united-arab-emirates-satellite

[11] https://futur.upc.edu/931337;https://futur.upc.edu/931345; https://futur.upc.edu/11151869;https://futur.upc.edu/11151863

[12] https://futur.upc.edu/33089728

[13] https://copernicus-masters.com/winner/ffscat-towards-federated-eo-systems/

[14] https://mosaic-expedition.org/profile/adriano-camps-2/

3. LIST OF PUBLICATIONS AND COPY OF THE MOST RELEVANT THREE.

All are Gold Open Access and all can be freely downloaded from the links provided (therefore, no printed copies are provided):

- Munoz-Martin, J. F.; Capon, L. F.; Ruiz-de-Azua J. A.; Camps, A. The Flexible Microwave Payload-2: A SDR-Based GNSS-Reflectometer and L-Band Radiometer for CubeSats, *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 13, pp. 1298-1311, 2020, doi: 10.1109/JSTARS.2020.2977959. https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9044708

- Munoz-Martin, J.F.; Fernandez, L.; Perez, A.; Ruiz-de-Azua, J.A.; Park, H.; Camps, A.; Domínguez, B.C.; Pastena, M. In-Orbit Validation of the FMPL-2 Instrument—The GNSS-R and L-Band Microwave Radiometer Payload of the FSSCat Mission. *Remote Sens.* **2021**, *13*, 121. https://doi.org/10.3390/rs13010121

- Ruiz-de-Azua, J.A.; Garzaniti, N.; Golkar, A.; Calveras, A.; Camps, A. Towards Federated Satellite Systems and Internet of Satellites: The Federation Deployment Control Protocol. *Remote Sens.* **2021**, *13*, 982. https://doi.org/10.3390/rs13050982

- Munoz-Martin, J.F.; Perez, A.; Camps, A.; Ribó, S.; Cardellach, E.; Stroeve, J.; Nandan, V.; Itkin, P.; Tonboe, R.; Hendricks, S.; Huntemann, M.; Spreen, G.; Pastena, M. Snow and Ice Thickness Retrievals Using GNSS-R: Preliminary Results of the MOSAiC Experiment. Remote Sens. 2020, 12, 4038. https://doi.org/10.3390/rs12244038

- Munoz-Martin, J.F.; Llaveria, D.; Herbert, C.; Pablos, M.; Park, H.; Camps, A. Soil Moisture Estimation Synergy Using GNSS-R and L-Band Microwave Radiometry Data from FSSCat/FMPL-2. *Remote Sens.* **2021**, *13*, 994. https://doi.org/10.3390/rs13050994

- Llaveria, D.; Munoz-Martin, J.F.; Herbert, C.; Pablos, M.; Park, H.; Camps, A. Sea Ice Concentration and Sea Ice Extent Mapping with L-Band Microwave Radiometry and GNSS-R Data from the FFSCat Mission Using Neural Networks. *Remote Sens.* **2021**, *13*, 1139. https://doi.org/10.3390/rs13061139

- Herbert, C.; Munoz-Martin, J.F.; Llaveria, D.; Pablos, M.; Camps, A. Sea Ice Thickness Estimation Based on Regression Neural Networks Using L-Band Microwave Radiometry Data from the FSSCat Mission. *Remote Sens.* **2021**, *13*, 1366. https://doi.org/10.3390/rs13071366

- Munoz-Martin, J.F.; Camps, A. Sea Surface Salinity and Wind Speed Retrievals Using GNSS-R and L-Band Microwave Radiometry Data from FMPL-2 Onboard the FSSCat Mission. *Remote Sens.* **2021**, *13*, 3224. https://doi.org/10.3390/rs13163224

4. CURRICULUM VITAE OF THE PRINCIPAL INVESTIGATOR

CV date	07/12/2021

Part A. PERSONAL INFORMATION

First name	Adriano José		
Family name	CAMPS CARMONA		
Gender (*)	Male	Birth date (dd/mm/yyyy)	18/10/1969
Social Security, Passport, ID number	46131105M		
e-mail:	adriano.jose.camps@upc.edu	URL Web: https://futur.upc.edu/AdrianoJoseCampsCarmona	
Open Researcher and Contributor ID (ORCID) (*)		0000-0002-9514-4992	

(*) Mandatory

A.1. Current position

Position	Full professor (catedrático de universidad)		
Initial date	20/03/2007		
Institution	Universitat Politècnica de Catalunya (UPC)		
Department/Center	Department of Signal Theory and Communications (TSC)		
Country	Spain	Telephone number	+34 934054153
Key words	Remote sensing, electromagnetism, microwave radiometry, GNSS-R, nanosatellites		

A.2. Previous positions (research activity interruptions, art. 14.2.b))

Period	Position/Institution/Country/Interruption cause
27/11/1997 - 19/03/2007	TITULAR DE UNIVERSIDAD/UPC/promotion to Full Professor
27/09/1993 - 26/11/1997	ASOCIADO/UPC/promotion to Prof. Titular (Associate Prof.)

A.3. Education

PhD, Licensed, Graduate	University/Country	Year
Telecommunications Engineer (1st of promotion)	Universitat Politècnica de Catalunya	1992
PhD in Telecommunications Engineering	Universitat Politècnica de Catalunya	1996

Part B. CV SUMMARY

Adriano Camps joined the Electromagnetics and Photonics Eng. Group, Dept. of Signal Theory and Communications, UPC, as an Assistant Professor in 1993, Associate Professor in 1997, and Full Professor since 2007. In 1999, he was on sabbatical leave at the Microwave Remote Sensing Lab., of the Univ. of Massachusetts, Amherst. His **research interests** are focused in: 1) microwave remote sensing, with special emphasis in microwave radiometry by aperture synthesis (PhD Thesis was about the MIRAS instrument which became the single payload of ESA's SMOS mission), 3) remote sensing using signals of opportunity (GNSS-R), 4) radio frequency interference detection and mitigation, and 5) nanosatellites as a tool to test innovative remote sensors. His **publication record** includes over 245 papers in peer-reviewed journals, 9 book chapters and the book Emery and Camps, "Introduction to Satellite Remote Sensing. Atmosphere, Ocean, Land and Cryosphere Applications," Elsevier, 2017, 860 pages), and more than 485 conference presentations. According to Google Scholar/Scopus his **h-index is 58 / 45**, and his publications have received more than **13252/9172 citations. According to the Stanford index, he is ranked in position 120.779 among all researchers worldwide in all research fields (percentile 1.3%).**

He holds **12 patents**, and has advised **27 Ph. D. Thesis students** (+ 8 on-going), and more than 150 final degree projects and M.Eng. Theses. These PhD students have now responsibility positions at Universities, companies and research centers. It is worth mentioning that 4 are at NASA/JPL, 1 at U. Michigan, and **2 have started their own companies (BALAMIS and MITICS) with A. Camps' participation**. A total of 5 patents have been transferred to them.

He is the **Scientific Coordinator of the CommSensLab Research Center** (María de Maeztu Excellence Research unit 2016-2020) at the Dept of Signal Theory and Communications. Within CommSensLab, he co-leads the Remote Sensing Lab (https://prs.upc.edu/), and leads the UPC NanoSat Lab (https://nanosatlab.upc.edu/en). He is the PI of the first four UPC nano-satellites: 1) ^{3}Cat-1: 1U CubeSat with 7 tech demos, 2) ^{3}Cat-2, a 6U CubeSat an innovative dual-frequency dual-polarization GNSS-R payload, 3) ^{3}Cat-4, a 1U Cubesat with a SDR implementing a microwave radiometer, a GNSS-Reflectomer, and AIS receiver, and 4) FSSCAT, a tandem mission formed by two 6U CubeSats. **FFSCat** is the **first mission contributing to the Copernicus System based on CubeSats** and it has produced for the first time using CubeSats scientific quality soil moisture, sea ice extent, concentration and thickness, and sea salinity maps in the Arctic.

He has participated in all Technical Committee Programs of the International Geoscience and Remote Sensing Symposium (IGARSS) since 2000, was Chair of uCal 2001, Technical Program Committee Co-chair of IGARSS 2007, co-chair of GNSS-R '10, general co-chair of IGARSS 2020, the 6th FFSS Workshop, and is member of the organizing committee of the ESA 4th Symposium on Space Educational Activities (SSEA).

He was Associate Editor of Radio Science, and the IEEE Geoscience and Remote Sensing Letters, and he is Associate Editor of the IEEE Transactions on Geoscience and Remote Sensing, and has been guest editor of several special issues. He was the President-Founder of the IEEE Geoscience and Remote Sensing Society (GRSS) Chapter at Spain, and 2017-2018 President of the IEEE Geoscience and Remote Sensing Society.

He has received several **awards** for his contributions to:

- **Research**: 1) 2nd National Award of University Studies (1993); 2) INDRA award of the COIT to the best PhD in Remote Sensing (1997); 3) UPC extraordinary Ph.D. Award (1999); 4) Research Distinction of the Generalitat de Catalunya (2002); 5) the European Young Investigator Award (2004), 6) the ICREA Academia award (2009, 2015), and 7) the grade of Fellow of the IEEE (2011).
- **Technology transfer**: As a member of the Microwave Radiometry Group, he received 1) the 1st Duran Farell award (2000) and 2) the Ciutat de Barcelona award (2001) for Technology Transfer, and 3) the "Salvà i Campillo" Award of the COETC for the most innovative research project for MIRAS/SMOS activities (2004), and 5) the 7th Duran Farell award for Technological Research for the work on GNSS-R instrumentation and applications (2010), 6) he and Mr. Querol received the ESNC Award-Barcelona Challenge for the FENIX system to detect and mitigate RFI in GNSS receivers (2015), and 7) the 2017 ESA Sentinel Small Satellite Challenge and the Overall Winner of 2017 Copernicus Masters Competition.
- **Education**: 1) Jaume Vicens Vives award 2012 (17/9/2012) from the Generalitat de Catalunya for the Project "Concepció, Disseny, Implementació i Operació de l'itinerari d'assignatures de projectes d'acord amb la iniciativa International CDIO", and 2) UPC award to the Teaching Quality at the University 2012 from the Social Council of the Universitat Politècnica de Catalunya (collective awards together with Profs. Bragós, Alarcón, Sayrol, Oliveras, and Pegueroles), and 3) IEEE Geoscience and Remote Sensing Society – Education Award 2021

Part C. RELEVANT MERITS *(sorted by typology)*

C.1. Publications *(see instructions)*

(selection among over 245, as of December 2021. Note: author order policy followed in my team = students go first, except if I was doing the main part of the work and the manuscript writing).

Some relevant publications (in reverse chronological order)

1. A. Alonso-Arroyo, V. U. Zavorotny and **A. Camps**, "Sea Ice Detection Using U.K. TDS-1 GNSS-R Data," in IEEE Transactions on Geoscience and Remote Sensing, vol. 55, no. 9, pp. 4989-5001, Sept. 2017, doi: 10.1109/TGRS.2017.2699122. (Number of citations 109)
2. **A. Camps**, H. Park, M. Pablos, G. Foti, C. P. Gommenginger, P.-W. Liu, and J. Judge, "Sensitivity of GNSS-R Spaceborne Observations to Soil Moisture and Vegetation," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 9, no. 10, pp. 4730-4742, Oct. 2016, doi: 10.1109/JSTARS.2016.2588467. (citations 151)
3. V. U. Zavorotny, S. Gleason, E. Cardellach and **A. Camps**, "Tutorial on Remote Sensing Using GNSS Bistatic Radar of Opportunity," in IEEE Geoscience and Remote Sensing Magazine, vol. 2, no. 4, pp. 8-45, Dec. 2014, doi: 10.1109/MGRS.2014.2374220. (Number of citations = 365)
4. E. Valencia, **A. Camps**, N. Rodriguez-Alvarez, H. Park and I. Ramos-Perez, "Using GNSS-R Imaging of the Ocean Surface for Oil Slick Detection," in *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 6, no. 1, pp. 217-223, Feb. 2013, doi: 10.1109/JSTARS.2012.2210392. (Number of citations = 84)
5. N. Rodriguez-Alvarez, D. M. Akos, V. U. Zavorotny, J. A. Smith, **A. Camps** and C. W. Fairall, "Airborne GNSS-R Wind Retrievals Using Delay–Doppler Maps," in IEEE Transactions on Geoscience and Remote Sensing, vol. 51, no. 1, pp. 626-641, Jan. 2013, doi: 10.1109/TGRS.2012.2196437 (Number of citations 94).

5 recent relevant publications (2020-present):

6. C. Herbert, **A. Camps**, F. Wellmann, and M. Vall-llossera, "Bayesian unsupervised machine learning approach to segment Arctic sea ice using SMOS data," Geophysical Research Letters, 2021, 48, e2020GL091285. https://doi.org/10.1029/2020GL091285 (Number of citations = 3)
7. **A. Camps**, "Spatial Resolution in GNSS-R Under Coherent Scattering," in IEEE Geoscience and Remote Sensing Letters, vol. 17, no. 1, pp. 32-36, Jan. 2020, doi: 10.1109/LGRS.2019.2916164. (Number of citations = 47)
8. H. Park, **A. Camps**, J. Castellvi and J. Muro, "Generic Performance Simulator of Spaceborne GNSS-Reflectometer for Land Applications," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 13, pp. 3179-3191, 2020 (Number of citations = 18)
9. J. F. Munoz-Martin, L. F. Capon, J. A. Ruiz-de-Azua and **A. Camps**, "The Flexible Microwave Payload-2: A SDR-Based GNSS-Reflectometer and L-Band Radiometer for CubeSats," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 13, pp. 1298-1311, 2020, doi: 10.1109/JSTARS.2020.2977959. (Number of citations = 19)
10. C. Molina**, A. Camps,** "First Evidences of Ionospheric Plasma Depletions Observations Using GNSS-R Data from CYGNSS," Remote Sens. 2020, 12, 3782. https://doi.org/10.3390/rs12223782 (Number of citations = 5)

C.2. Conferences

A total of 485 conference presentations have been presented, a vast majority (> 95%) in international conferences and symposia (e.g. IGARSS, URSI, MicroRad, GNSS+R…), and every year about 5 of these presentations are by invitation. Further results can be consulted at: https://futur.upc.edu/AdrianoJoseCampsCarmona/as/cHJlc2VudGFjaW90cmViYWxscHJlc2VudGF0ZW5jb25ncmVz#produccio
Which only includes the ones with proceedings deposited in an Open Access repository.

C.3. Research projects (5 most significant ones)

EU:

1. Operational Network of Individual Observation Nodes, H2020-687490-ONION, Participatnts: TAS-F, TAS-E, DEIMOS ENGENHARIA, ACRI-ST SAS, UPC, SkolTech, Politechnika Warzawska, SpaceTec Partners SPRL, duration: 1/1/2016-31/12/2017, Grant: **125.000 €** (UPC) + OH, **IP:** S. Pierotti (TAS-F), **A. Camps (UPC Remote Sensing Lab coordinator)**,

2. **European GNSS-R Environmental Monitoring,** FP7-607126-E-GEM, Participatnts: Deimos Eng. (Pt.)-coordinator, UPC (Sp), ICE/CSIC (Sp), U. Salamanca (Sp), U. Tor Vergata (It), U. La Sapienza (It), IFREMER (Fr), NERSC (No), NORUT (No), duration: 1/12/2013-1/11/2016, Grant: **335.775 €** (UPC), **IP:** N. Catarino (Deimos Eng), **A. Camps (UPC coordinator)**,

ESP

1. **Sensing with Pioneering Opportunistic Techniques (SPOT)** – Subproject UPC, MICINN RTI2018-099008-B-C21, Participants: UPC (coordinator), ICE/CSIC; duration: 01/01/2019-31/12/2021, Grant: **155.300** € (UPC), **IP: A. Camps (IP coordinador)**, Number of researchers: 2 research team (UPC) + 4 working team
2. **Técnicas avanzadas en teledetección aplicada usando señales GNSS y otras señales de oportunidad, MINECO** ESP2015-70014-C2-1-R, Participants: UPC (coordinator), ICE/CSIC; duration: 1/2016-12/2018; Grant: **160.000 €** (UPC) + 220.000 € (ICE) + OH, **IP: A. Camps (IP coordinator)**, Number of researchers: 7 (UPC) + 6 (ICE/CSIC)
3. **Aplicaciones Avanzadas en Radio Ocultaciones y Dispersometría Utilizando Señales GNSS y otras Señales de Oportunidad**, MINECO AYA2011-29183-C02-01, Participants: UPC (coordinator), ICE/CSIC; duration: 1/2012-12/2014; Grant: **730.000 €** (UPC) + 592.900 € (ICE) + OH, **IP: A. Camps (IP coordinator)**, Number of researchers: 7 (UPC) + 6 (ICE/CSIC)

C.4. Contracts, technological or transfer merits

Mostly with the European Space Agency (ESA) directly or as part of a consortium working for ESA:

1. **Biomass End-to-End Performance Simulator Front End** (BEEPS-FE) **Ionospheric Module** (IOM), (DLR > Airbus Defense and Space > ESA) Duration: 10/2019-2/2023. Participants: A. Camps (PI)IEEC/UPC(ES), and RDA (CH) as subco. Amount: 125 k€ (UPC)+125 k€ (RDA)
2. **Ionosphere Impact and Corrections for Low Frequency Radars** (ONERA > ESA), Duration: 1/2021-8/2022. Participants: ONERA(FR)+IEEC/UPC(ES)+RDA(CH). UPC subcontract: 65 k€
3. **FFSCAT** (Deimos Eng > ESA)**,** 2017 ESA Sentinel Small Satellite Challenge and overall Copernicus Masters Competition winner (A. Camps, A. Golkar), Duration: 11/2017-3/2021. Participants: UPC (ES) – **A. Camps** (PI), Deimos Eng (PT), Golbriak (EE), Cosine (NL), Tyvak Int’l (IT), Total amount: 1.000.000 € (total, 180.000 € UPC)
4. **Potential of Spaceborne GNSS-R for Land Applications** (La Sapienza > ESA), ESA/ESTEC CONTRACT n. 4000120299/17/NL/AF/hh, Duration; 19-6-2017 to 18-09-2019, Participants: UPC (ES) 30.000 €, U. Tor Vergata, Starlab, Deimos UK, coordinator U. La Sapienza (IT)
5. **BIBLOS-2: MODEL LIBRARY FOR EARTH OBSERVATION END-TO-END SIMULATORS,** (GMV > ESA) ESTEC Contract 4000118711, duration: 16/11/2016-16/5/2019, Participants: GMV Poland, GMV Spain, UPC IP (UPC): **A. Camps**, Number of researchers: 3 (UPC), Amount: 35 k €
6. **GEROS-International Space Station** (Airbus > ESA), duration: 5/12/2014 to 24/3/2016, IP: **A. Camps (coordinator UPC+ICE/CSIC)**, Amount: 36.5 k€
7. **GARCA** (GFZ > ESA), Duration: 30/7/2014-1/11/2015, Deimos Eng (Pt),CLS (Fr), IFREMER (Fr), IEEC (Sp), NERSC (No), NOC (UK), IP: E. Cardellach (coordinator UPC+ICE/CSIC), Number of researchers: 2 (UPC) + 3 (ICE), Amount: 72.450 k€
8. **PARIS IoD Phase A** (EADS CASA Espacio > ESA), Duration: 6/2011-12/2012, Participants: IP: **A. Camps (coordinator UPC+ICE/CSIC)**, Amount: 85 k€

In addition to the above projects, we are currently working for:

9. **INDRA** in an ESA project (**GNSS Reference Station Environment Monitoring Unit** (RF-SESMS) - Program/System: H2020-ESA-015.11-Work Order 4 to design a system for radio frequency interference detection and localization to support the optimization of the GALILEO ground stations.

10. **Thales Alenia Space – España** as consultors for the design of the radio frequency front-ends of the **Copernicus Imaging Microwave Radiometer** (CIMR), the Earth Explorer 11 mission.

Additionally, A. Camps holds 12 patents issued from the previous research projects (Section C3). From these, 4 patents have been transferred to BALAMIS, and 1 patent to MITICS. BALAMIS and MITICS are spin-off companies started by former PhD students of A. Camps, and co-founded by Prof. Camps.

The above list of contracts shows the commitment with the Spanish and European industry to transfer the know-how developed in the research projects (Section C3) into products, systems, and satellite missions that benefit the whole society. This commitment has been rewarded with some awards for Tech Transfer (see Section B).

Final note: ***It is the wish of the team members of this candidacy that -in case of being awarded the 13th Duran Farell Award- the award be transferred to an internal UPC account to support the activities of the UPC NanoSatLab.***

ADDITIONAL MATERIALS

Videos:

- FSSCat Mission Video:
    - https://youtu.be/lQAaoYUPluA (long)
    - https://twitter.com/i/status/1301766892261175296 (short)
- Interviews on FSSCat with Director of the Fundació Catalana per la Recerca i la Innovació:
    - https://youtu.be/uVN_JekoZzQ
    - https://youtu.be/1VY5f56b80U

ESA web links:

- https://www.esa.int/Applications/Observing_the_Earth/Ph-sat/FSSCat_F-sat-1_ready_for_launch
- https://www.esa.int/ESA_Multimedia/Images/2017/11/FSSCat
- https://www.esa.int/ESA_Multimedia/Images/2020/06/Barcelona_Spain
- https://www.esa.int/ESA_Multimedia/Videos/2020/06/Earth_from_Space_Barcelona
- https://earth.esa.int/eogateway/news/introducing-the-newest-esa-third-party-missions

UPC web links:

- https://www.upc.edu/en/press-room/news/in-orbit-the-mission-fsscat-of-the-nanosat-lab
- https://www.upc.edu/en/press-room/news/the-upc2019s-nanosat-lab-demonstrates-feasibility-using-nanosatellites-to-observe-the-earth-and-climate-change
- https://telecos.upc.edu/ca/noticies/xerrada-fsscat-la-primera-missio-basada-en-cubesats-que-contribueix-al-sistema-copernicus-de-la-concepcio-de-la-missio-a-la-generacio-de-mapes-dhumitat-i-gel-16-desembre

Other links:

- https://www.ccma.cat/324/senlairen-per-primer-cop-dos-nanosatellits-catalans-amb-intelligencia-artificial/noticia/3044798/
- https://www.lavanguardia.com/ciencia/20200622/481840275798/despegue-cohete-vega-satelites-espanoles-upc.html
- https://www.lavanguardia.com/natural/20200612/481721096592/asi-ve-barcelona-satelite-europeo-observacion-terrestre.html
- https://www.lavanguardia.com/ciencia/20200704/482060144034/adriano-camps-nanosatelites-catalunya-upc.html
- https://www.lavanguardia.com/edicion-impresa/20200704/482070493903/nanosatelites-made-in-catalunya-adriano-camps.html
- https://www.facebook.com/IEEE.GRSS/posts/3203282033059053

APPENDIX:

SUPPORT LETTER FROM MR. MIGUEL BELLÓ (CEO AIRCENTRE, COMMISSIONNER OF AEROSPACE PERTE)

AIR CENTRE
ATLANTIC INTERNATIONAL RESEARCH CENTRE

Support Letter to Prof. Adriano Camps for the Duran Farell Award on Technology Transfer

June 22nd 2022

To whom it may concern:

As CEO of the Atlantic International Research (AIR) Centre, inter-governmental organization dedicated to the development of ocean, atmospheric and space based technological applications towards the achievements of the sustainability goals of UN and the mitigation of climate change issues, I would like to send this support letter to **Prof. Adriano Camps** for the Duran Farell Award on Technology Transfer.

We firmly believe that Prof. Camps deserves this prestigious Award, not only for the successful work in the field of Cubesats and the FSSCat project, but also for the development of the very promising GNSS-R (Global Navigation Satellite System Reflectometry) Technology notably for ocean and land applications. We believe that the outcomes of his work significantly contribute to the consolidation and further development of new techniques that are creating a revolution in Earth Observation, of great interest to the AIR Centre, even more in the advent of the Spain-Portugal "Atlantic Constellation" that plans to carry GNSS-R payloads in the near future, project that was proposed by the AIR Centre to above countries.

Yours sincerely,

Dr. Miguel Belló Mora

Chief Executive Officer (CEO)

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