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## Nanosatellites for Astrophysics

Boris Segret

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*Habilitation à Diriger des Recherches*

**DE L'UNIVERSITÉ PSL**

Préparée à Paris Observatory-PSL

**Thesis for the Accreditation to Supervise Research  
(English translation)**

**Nanosatellites for Astrophysics**

Soutenue par

**Boris SEGRET**

Le July 4, 2024

École doctorale n°127

**Astronomy and  
Astrophysics of  
Île-de-France**

Spécialité

**Astrophysics**

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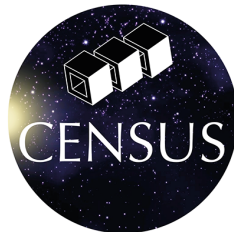
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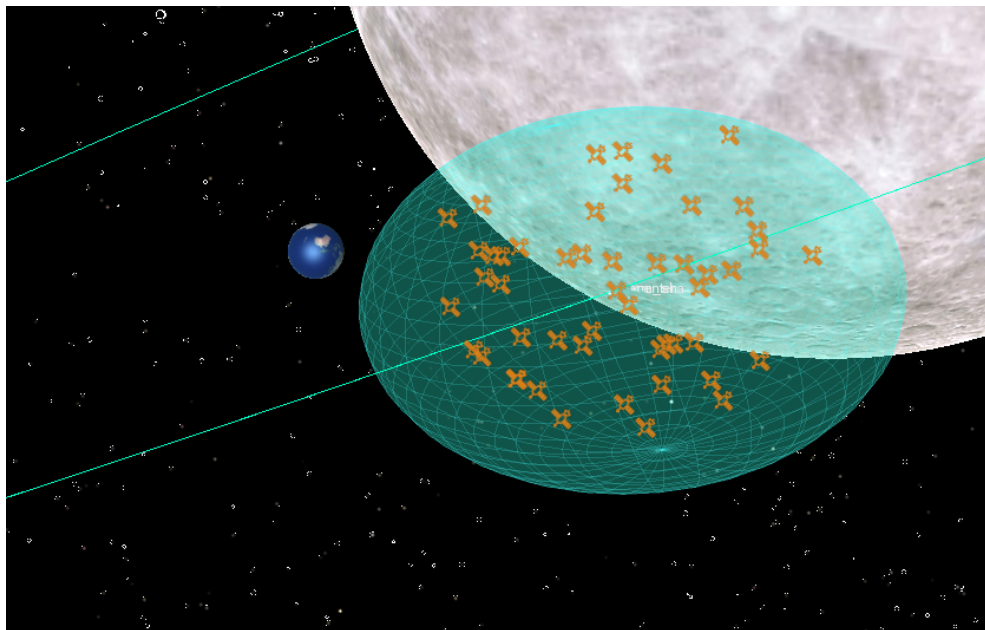


# NANOSATELLITES FOR ASTROPHYSICS

THESIS FOR THE ACCREDITATION TO SUPERVISE RESEARCH  
(“HDR”, FRENCH DEGREE),  
CONDUCTED WITHIN THE FRAMEWORK OF CENSUS



SPACE CENTER OF PSL UNIVERSITY,  
EXPERTISE HUB OF PARIS OBSERVATORY-PSL



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<sup>1</sup>figure 4.6 in §4.2



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*to my wife Chia-Ling, with a shared thought for Phébus  
to my sister Leïla  
to my friend Paul*

δός μοί ποῦ στῶ, καὶ κινῶ τῆν γῆν

*attributed to Archimedes by Pappus of Alexandria, according to Ver Eecke [1]*

## **Acknowledgments**

So many of you have supported me to reach this stage, both before and after my thesis, that singling out one person would unjustly leave others in the shade. I do mention my dear wife, Chia-Ling, who has been with me every day. We must also thank all our predecessors, whose thoughts have propagated over the centuries and formed a foundation upon which we continue to advance. My own journey has taken a few detours but is primarily shaped by encounters. Will I enable others to go further? Nothing today, without our predecessors yesterday. Nothing of what I am today, without all of you, all around.

*Le « NewSpace » est formidable. Connue pour ses méga-constellations de nanosatellites autour du globe, la surveillance en continu des incendies, le repérage de navires illégaux ou bientôt l'échange de clés cryptées. C'est donc un foyer d'innovations avec de belles opportunités de financement. Mais l'astrophysique, dont l'importance politique ne se dément pas dans l'ère moderne, reste le parent pauvre de ce changement de paradigme, faute de débouchés commerciaux immédiats. Pourtant, je suis convaincu qu'il faut encore et toujours monter en compétences dans ce domaine pour que les décisions de financement s'imposent naturellement. Ce mémoire pour demander l'habilitation à diriger des recherches est donc un acte politiquement engagé. J'y exposerai mon expérience industrielle et mon arrivée dans le spatial scientifique, qui coïncide avec le lancement du premier nanosatellite français en 2012, se poursuit avec les premiers CubeSats interplanétaires en 2018 et, désormais, une première armada vers la Lune et l'astéroïde double Didymos. Il y a fort à parier que toutes les missions d'exploration offriront désormais des opportunités pour des nanosatellites, donc aussi des opportunités de développements technologiques rapides pour les équipes de recherche en astrophysique. Avec mes mentors Pierre Drossart et Jean-Pierre Lebreton dans les années 2015, nous avons fait ce pari et choisi d'investir à long terme sur les nouvelles compétences requises pour des nanosatellites de qualité scientifique, car un « CubeSat » est loin d'être un satellite en kit: il fallait des méthodes, des outils et des équipements dédiés, autrement dit un écosystème, devenu bientôt pôle d'expertise de l'Observatoire de Paris - PSL. Cet environnement m'a permis de co-encadrer 4 doctorants, 9 ingénieurs et 45 étudiants en stages de fin d'études de DUT ou de Master. J'y ai conçu un support d'ingénierie original, au profit de plus de 7 équipes de recherche sur leur projet de nanosatellite scientifique. J'y ai mis en place quelques partenariats avec l'industrie. L'intérêt d'une HDR est donc, pour moi désormais, de promouvoir les spécificités des nanosatellites pour l'astrophysique, et ceci aux plus hauts niveaux académiques, afin que les ingénieurs et docteurs ainsi formés produisent à leur tour du Savoir et des savoir-faire.*

**Mots clés :** *ingénierie spatiale, espace profond, radio-astronomie, planétologie, cosmologie, physique stellaire, météo de l'espace, géodésie, interplanétaire, exploration spatiale, autonomie, nanosatellites, CubeSat*



## Abstract

“NewSpace” is great. Known for its mega-constellations of nanosatellites around the globe, continuous monitoring of fires, tracking of illegal vessels and, soon, the exchange of encrypted keys. It’s a hotbed of innovation, with excellent financing opportunities. But astrophysics, whose political importance is undeniable in the modern era, remains the poor cousin of this paradigm shift, due to a lack of immediate commercial outlets. And yet, I’m convinced that we still need to build up our skills in this field, so that funding decisions can be taken as a matter of course. This dissertation is therefore a politically committed act. In it, I will describe my industrial experience and my arrival in scientific space, which coincides with the launch of the first French nanosatellite in 2012, continues with the first interplanetary CubeSats in 2018 and, now, a first armada to the Moon and the double asteroid Didymos. It’s a safe bet that all exploration missions from now on will offer opportunities for nanosatellites, and therefore also opportunities for rapid technological developments for astrophysics research teams. With my mentors Pierre Drossart and Jean-Pierre Lebreton in 2015, we took this gamble and chose to make a long-term investment in the new skills required for scientific-quality nanosatellites, because a “CubeSat” is far from being a kit satellite: dedicated methods, tools and equipment were required, in other words an ecosystem, which soon has become a center of expertise at Observatoire de Paris - PSL. This environment enabled me to co-supervise 4 PhD students, 9 engineers and 45 students in their final year of a BTS or Master’s degree. I designed an original engineering support for more than 7 research teams on their scientific nanosatellite project. I also set up a number of partnerships with industry. For me, the purpose of an HDR is now to promote the specificities of nanosatellites for astrophysics, at the highest academic levels, so that the engineers and PhDs thus trained in turn produce knowledge and know-how.<sup>2</sup>

**Keywords:** space engineering, Deep space, radio-astronomy, planetology, cosmologie, stellar physics, space weather, geodesy, interplanetary, space exploration, autonomy, nanosatellites, CubeSat

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<sup>2</sup>DeepL.com and ChatGPT/Openai were used to translate this document from French.



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At my age, one becomes rushed again, always out of excitement and increasingly out of lack of time. Thus, I defend my “Habilitation à Diriger des Recherches” (Accreditation to Supervise Research) (HDR) only 5 years after my thesis. Being a late vocation in space science, it is in light of my entire career that I present this manuscript. I update my scientific theme from my 2019 thesis and my work plan (Chap. 2), because there is still much to be done.

We will examine the extent of the famous “NewSpace paradigm” for astrophysics, abroad and in France, in Chapter 3. The assessment will be severe: we may well miss this rocket! Of course, along with others, I aim to elevate our expertise in this field, which is the purpose of this HDR. But we will not be sufficient if the race for innovation continues to dry up the R&D that astrophysics carries within it. We will also see that injunctions can hinder the emergence of novel observational strategies.

Indeed, I have had the privilege of accompanying several researchers in their original strategies, which we will review (Chap. 4), from the exploration of small celestial bodies to cosmology. Immersion in these various projects has led me to establish an entire ecosystem (Chap. 5), today named CENSUS, initially created by Pierre Drossart, DR, and later becoming an expertise hub of Paris Observatory-PSL under the leadership of Coralie Neiner, DR. My role as technical director will be presented there: engineering support with an original approach labeled Model-Based System Engineering (MBSE), a term I claim despite its potential controversy; collection of commercial off-the-shelf nanosatellite systems; “internal” projects like the PROMESS platform, the VEGA clean room, or the ground station. I could not have done all this alone, and my supervisory role will also be discussed, mostly involving training *through* Research. Finally, my contributions to the community, not directly related to my work, will be summarized in Chapter 6: conferences, committees, but also financial support, always in the name and thanks to CENSUS.





- AbC** Angle-based Correlation (CENSUS embedded astrometry algorithm).
- AI** Artificial Intelligence.
- AIT/AIV** Assembly, Integration and Tests / Assembly, Integration and Validation.
- APC** Astroparticle and Cosmology Laboratory, Université Paris Cité.
- C<sup>2</sup>ERES** Center and Campus for Space Exploration Studies and Research, former name of CENSUS.
- CCSDS** Consultative Committee for Space Data Systems Data Exchange Format and Protocol.
- CENSUS** Centre for Nanosatellites in Sciences of the Universe, expertise hub of Observatoire de Paris-PSL, PSL's space center.
- CI/CD** Continuous Integration / Continuous Deployment.
- CNES** Centre National d'Études Spatiales (French National Centre for Space Studies).
- CNRS** Centre National de la Recherche Scientifique (French National Centre for Scientific Research).
- COTS** Commercial-Off-The-Shelf, sometimes also Component-Off-The-Shelves.
- CPU** Central Processing Unit.
- Cubesat** Small satellite form factor adhering to the standard published by cubesat.org.
- DOCKS** Design and Operations Cross-checking Services, CENSUS open-source software suite.
- DSN** Deep Space Network, NASA.
- ENS** École Normale Supérieure, PSL.
- ENSAD** École Nationale Supérieure des Arts Décoratifs, PSL.
- ESA** European Space Agency.

- ESOC** European Space Operations Center, ESA, Darmstadt (Germany).
- ESRIN** European Space Research Institute, ESA, Frascati (Italy).
- ESTRACK** European Space Tracking, ESA.
- GRGS** Groupe de Recherche de Géodésie Spatiale (Space Geodesy Research Group).
- HDR** “Habilitation à Diriger des Recherches” (Accreditation to Supervise Research).
- IFOD** In-Flight Orbit Determination.
- IMCCE** Institute of Celestial Mechanics and Ephemeris Calculation, Observatoire de Paris-PSL.
- ISRO** Indian Space Research Organisation.
- JPL** Jet Propulsion Laboratory, NASA, Los Angeles (CA/USA).
- L $\mu$ PPT** Liquid micro-Pulsed Plasma Thruster.
- LabEx ESEP** Laboratory of Excellence for Space Exploration of Planetary Environments, French national program for future investments.
- LERMA** Laboratory for the Study of Radiation and Matter in Astrophysics and Atmospheres, Observatoire de Paris-PSL.
- LESIA** Laboratory of Space Studies and Instrumentation in Astrophysics, Observatoire de Paris-PSL.
- LISA** Interuniversity Laboratory of Atmospheric Systems, Univ. Paris-Est Créteil.
- M.I.T.** Massachusetts Institute of Technology, Boston (MA/USA).
- MBSE** Model-Based System Engineering.
- NASA** National Aeronautics and Space Administration.
- NCKU** National Cheng Kung University, Tainan, Taiwan.
- NCU** National Central University, Jhongli, Taiwan.
- OBC** On-Board Computer.
- ONERA** French national aerospace research centre.
- OSAE** Tools and Systems for Astronomy and Space, Master’s program at Observatoire de Paris-PSL.
- P.I.** Principal Investigator.
- PDR** Preliminary Design Review.
- P-POD** Poly Picosatellite Orbital Deployer.
- PSL** Université Paris Sciences & Lettres.
- R&T** Research and Technology, as opposed to “innovation”.
- SADT** *Structured Analysis and Design Technique*.

**SwRI** Southwest Research Institute.

**TU** *Technische Universität* (en Allemagne).

**TU Delft** *Delft University of Technology*, Pays-Bas.

**UFE** Unité de Formation et d'Enseignement, Observatoire de Paris-PSL.



## 2.1 Detailed Curriculum Vitae

### Boris SEGRET

- Personal address: 1 rue de Béarn, 92210 Saint Cloud, France.
- Professional address: Observatoire de Paris-PSL / CENSUS, 5 place Jules Janssen, 92195 Meudon Cedex, France. Tel.: +33.1.4507.7824.  
Email: Boris.Segret@ObservatoireDeParis.psl.eu

### Education

- 25/09/2019: Ph.D. in Astronomy and Astrophysics, Université Paris Sciences et Lettres, prepared at Observatoire de Paris within the Doctoral School Astronomy and Astrophysics of Île-de-France, titled "Embedded Algorithm for Autonomous Optical Navigation for Interplanetary Nanosatellites."
- 2011: Master's degree in "Tools and Systems in Astronomy and Space," specializing in astronomy, astrophysics, and space engineering, from Observatoire de Paris.
- 1991: Engineer's degree from École Nationale Supérieure de Mécanique et d'Aérotechnique de Poitiers, ISAE-ENSMA.
- 1985: Baccalauréat (French high school diploma), specialized in science (series C), with preparatory classes at Lycée Henri IV, Paris.

### Professional Experience

**09/2013-Present**, OBSERVATOIRE DE PARIS-PSL, Meudon (92) – System Engineer and then Technical Director of CENSUS (2020), the space pole of PSL, an expertise hub of Observatoire de Paris: support for projects of the Laboratory of Excellence for Space Exploration of Planetary Environments, French national program for future investments (LabEx ESEP) network (a network of 9 space laboratories in Île-de-France, until 2020); creation and implementation of engineering support for PSL's nanosatellite projects, through engineering methods, nanosatellite systems, testing and operational means, development of national and international collaborations, supervision of 4 doctoral students, 8 engineers, and 45 interns, various educational contributions.

## 2.1. DETAILED CURRICULUM VITAE

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**08/2011-08/2013**, LATMOS - CNRS, Guyancourt (78) – Operations Engineer for the SPI-CAV instrument on the VENUS EXPRESS/ESA orbiter for UV, NIR, IR in-situ spectrometry of the Venus atmosphere: command planning and programming; system engineering for phase E; scientific computing (including JPL/NASA SPICE).

**03-08/2011**, INSTITUT D'ASTROPHYSIQUE SPATIALE, Orsay (91) – Feasibility study of stable pointing of Jupiter through onboard image analysis, as part of an instrument proposal for JUICE, an ESA space mission (Master's internship).

*(2007-2011, career transition and return to studies)*

**09/2003-05/2007**, EADS ASTRIUM SPACE TRANSPORTATION (now ArianeGroup), Les Mureaux (78) – Project Buyer Engineer: negotiation and drafting of purchase contracts for the "PA series" for ARIANE 5 propulsion (30 launchers, solid propulsion with EUROPROPULSION, liquid propulsion with SNECMA now SAFRAN), then for various systems with EADS CASA ESPACIO and ASTRIUM SATELLITES.

**1999-2003**, KADRAS LTD., Versailles (78), Athens (Greece) – Establishment of a consulting offer in strategy and software project management, negotiation and coordination support.

**1991-1999**, DASSAULT AVIATION, Saint Cloud (92), Vélizy-Villacoublay (78), Teterboro (USA/NJ) – Successively, flight control engineer for RAFALE M, integration of EM and IR countermeasures systems and electromagnetic compatibility on MIRAGE 2000 N&D and RAFALE, customer support for integrated maintenance on FALCON business jets.

**1991 (9 months)**, RHEINISCHE-WESTFALISCHE TECHNISCHE HOCHSCHULE, Aachen (RWTH, Germany) – Third year of engineering school abroad, internship in aerodynamics laboratory and aerodynamics curriculum at RWTH.

**1990 (6 months)**, DASSAULT AVIATION, Saint Cloud (92) – Internship engineer in theoretical aerodynamics, calculation architecture for multi-scale and multi-code aerodynamic meshing (typically Euler and Navier-Stokes).

**1989 (2 months)**, HARTING AG, Biel (Switzerland) – Intern worker in electronic connector production factory: plastic thermoforming, micro-cutting and metal folding, galvanization, quality control.

### Research and Valorization Activities

- MBSE methodology applied to concurrent engineering
- System engineering support for mission profiles of the following projects:
  - BIRDY-T (Obs.Paris-PSL, IMCCE), spatial geodesy of asteroids
  - CASSTOR (Obs.Paris-PSL, LESIA), UV spectro-polarimetry of stars
  - CURE (Obs.Paris-PSL, LESIA), exoplanet transit ephemerides
  - TERACUBE (Obs.Paris-PSL, LERMA), Venus atmosphere in THz
  - COSMOCAL (ENS-PSL), spatial calibration target for CMB measurements
  - CIRCUS (Obs.Paris-PSL, LESIA), dynamics of the Earth's ionosphere

- SCION-X (NCU, Taiwan), atmospheric pollution monitoring
  - TUDsat (TU Darmstadt, Germany), laser telecommunication demonstration
- Co-development of an open-source software suite for mission prototyping "DOCKS"
- Interplanetary navigation algorithm during cruise and proximity operations: orbit determination (IFOD), in-flight image processing (AbC), artificial intelligence, CPU measurement
- Valorization of IFOD with companies ODYSSEUS (Luxembourg) and D-FINE GMBH (Germany), and AbC with EUTELSAT GROUP
- Flight tests on OPS-SAT nanosatellite from ESA/ESOC (Darmstadt, Germany)
- Shared use of Commercial-Off-The-Shelf, sometimes also Component-Off-The-Shelves (COTS) systems and AIT/AIV experience within PSL, then in CNRS research federation "Nanosatellites"
- Co-design of a Concurrent Engineering Platform "PROMESS", a clean room "VEGA", specialized tooling "FLATSAT" for AIT/AIV
- Co-design with EUTELSAT GROUP of a ground station interoperability infrastructure for nanosatellites "NANOSATGRID"
- Member of project review committees for:
  - PICSAT (LESIA, CNRS), technological demonstration, exoplanetary transit monitoring
  - IGOSAT (APC, Univ. Paris Cité), GPS signal occultation
  - SCION-X (NCU, Taiwan), atmospheric pollution monitoring
  - CROCUS (ONERA), electrostatic discharge monitoring in orbit
- Member of the scientific committee of the Nanosatellites Research Federation (CNRS)

### **Teaching and Supervision Activities**

#### **Theses**

- Co-supervision of Gary QUINSAC, supervised by B. Mosser, "From Commercial-Off-The-Shelf to expected propulsion in nanosatellites", 2015-2019
- Co-supervision of The Huynh HOANG, supervised by B. Mosser, nanosatellite attitude control test tooling, 2016-2017 (interrupted)
- Co-supervision of Erwan ROUILLÉ, supervised by B. Cecconi, "NOIRE: a distributed radio imager in space", ongoing
- Co-supervision of Janis DALBINS from 2020, with A. Slavinskis, thesis supervised by M. Noorma at the Tartu Observatory (Estonia), "Telecom experiments for deep space exploration with nanosatellites", 2016-2024
- Member of the thesis monitoring committee for Ryan DAHOUMANE, co-supervised by V. Lainey and K. Baillé at IMCCE, "Long-term dynamic evolution of outer satellites of Jupiter and Saturn" (ongoing)



## 2.1. DETAILED CURRICULUM VITAE

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- Reviewer of the doctoral thesis manuscript of Eleonora ANDREIS, thesis supervised by F. Topputo at Politecnico di Milano (Italy), "Autonomous Vision-Based Navigation for Deep-Space CubeSats: Algorithm Development and Hardware Validation", 2024

Supervision of 8 engineers and 1 assistant engineer: Janis DALBINS (IR, 1+ year, ongoing), Sébastien DURAND (IE, 2 years), Grégoire HENRY (IE, 3 months), Thibault DELRIEU (IE, 3 months), Louis LE LEUCH (IE, 3 months), Rashika JAIN (IE, 2 years), Feliu LACREU (IE, 13 months), Pedro da FONSECA (IE, 13 months), Kirill ANOHIN (AI, 13 months)

Supervision or co-supervision of 45 long internships (3-6 months): list in appendix

Supervised, co-supervised, or mentored educational topics:

- Project modules of the Master OSAE "Tools and Systems of Astronomy and Space" at Observatoire de Paris-PSL / UFE: 1 to 2 subjects/year in pairs, since 2014.
- "Lab. Insertion Unit" modules of the Astrophysics graduate program at PSL (M1) and MasterClass (M2), 10-day subjects, since 2021.
- Mentoring for PSL-ITI, then PSL-iTeams (PSL's pre-doctoral and entrepreneurial track): 4 mentored subjects.
- Mentoring at engineering schools CentraleSupélec, Centrale Lille, ELISA: 5 subjects from 2013 to 2016.
- Seminars at the Astronomy and Biology Summer Schools in Tartu (Estonia) 2018 and 2019
- Seminar at the GRGS Summer School 2016

### **Communications & Publications** (list appended)

- Articles, proceedings, and posters: 32, including 9 as first author
- Oral communications without publication: 53, including 28 as first author

### **Outreach Activities**

- PSL Week: Animation of 2 one-week sessions on the theme of exoplanets
- NEX'ORBITER, development of a networked video game on space flight
- Association Planète Mars: board member (2008-2020), public lectures, book chapter on scientific issues, Radio France Inter on the arrival of Curiosity (08/06/2012)
- Public article on nanosatellites in *The Conversation France* (06/15/2020)
- Radio France Culture on my thesis for BIRDY (05/09/2018)
- Hosting the "Interplanetary CubeSat Workshop" 2018 in Paris

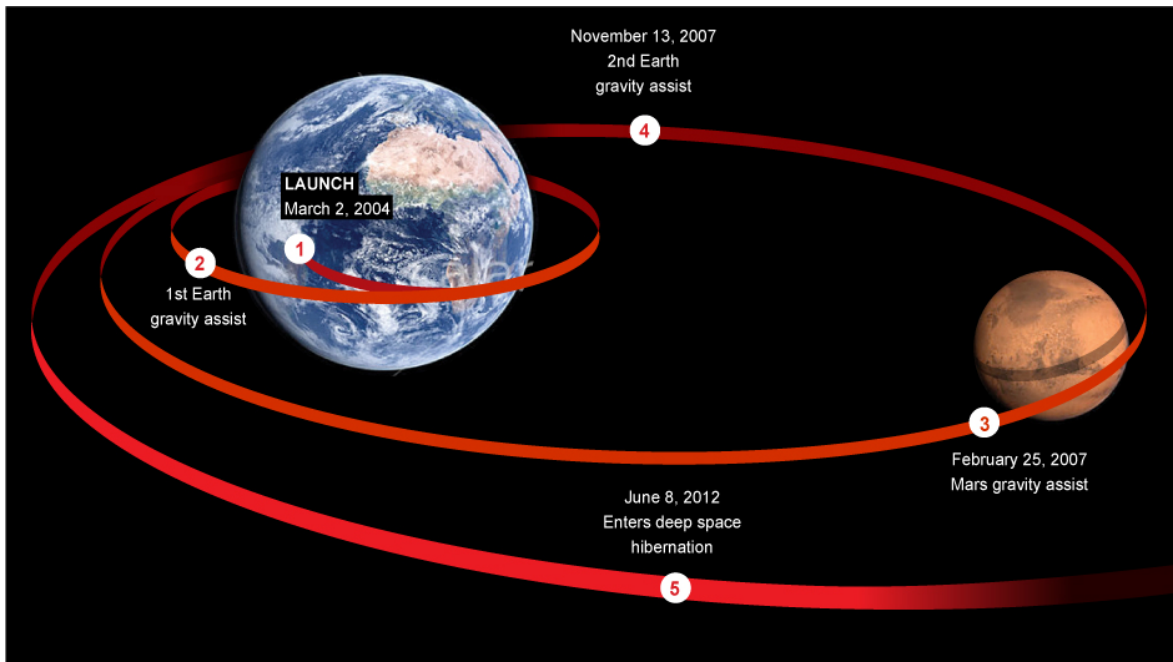


Figure 2.1: On March 2, 2004, ARIANE 518 placed ROSETTA on a 10-year interplanetary trajectory (illustration: [www.telegraph.co.uk](http://www.telegraph.co.uk), 08/05/2014).

## 2.2 From Industry to Science

In France, becoming an engineer has long been portrayed as an ideal, providing access to all possible professions, a curriculum for the elite. Until the 1990s, the degree indeed guaranteed job access, often through pre-contracts offered by the industry. This was my case, with DAS-SAULT AVIATION, where I had the chance to discover a wide range of engineering professions early in my career, thus preparing me from the outset to become a systems engineer. But these were also the early years when freshly graduated engineers experienced unemployment. Feeling fortunate to have escaped this, I regarded industry as the only worthwhile professional horizon, perpetuating this typically French arrogance towards academia.

However, times were changing rapidly. For me, it took more than 10 years. In the 2000s, while at EADS Space Transportation (now ARIANEGROUP), I ventured into combining my engineering background with commercial negotiation. On March 2, 2004, I witnessed from the Mureaux site (78, Yvelines) the live broadcast of the ARIANE 5, flight 518 (or VA158): ARIANE launched ROSETTA on a 10-year interplanetary trajectory (Fig. 2.1)<sup>1</sup>. The tension was palpable, especially since the previous flight failure had resulted in the loss of the HOT BIRD 7 satellite from “our” client Eutelsat. But I also wondered who had actually developed the instruments of ROSETTA that “we” were launching into space that day. Shamefully, I was unaware that hundreds of researchers and engineers had been working for decades in public research laboratories to create spacecraft instruments: where had my blinders come from? In these labs, risky technologies are developed, which are later adopted by the industry if a market emerges; this is where instrumentation experts design them and researchers conceive them to collect data that are crucial for often fundamental scientific questions. It’s worth noting that 30% of these brilliant researchers’ time - the real captains of the ship - is spent seeking funding to support these projects and thus finance... the industry, thereby driving the entire economy. Yet, calls continue to circulate demanding that scientists be more closely

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connected to the “real economy” (sic).

When I joined scientific space missions in 2011, I encountered educators at the forefront of technology, often ahead of it (I recall exercises from the OSAE Master’s on neural networks for image processing, at a time when the internet had not yet addressed AI). There, I met PhD students and researchers, mostly from public universities, French or foreign, who were thinking faster and perhaps better than the experienced engineer I already was. I discovered the role of a Principal Investigator (Principal Investigator (P.I.)) and the scientific, instrumental, and managerial versatility it entails, which commands respect. I also rediscovered system engineering methods that I had learned at DASSAULT AVIATION and were being practiced here for complex astronomy systems; however, I also rediscovered them in all their documentary heaviness, but this is the price of product assurance and quality assurance.

### 2.3 Revisiting System Engineering

During this time, I actively promoted manned flights to Mars (at the French Chapter of the *Mars Society*) and attended conferences on *Mars Sample Return*. I also noted the emergence of Cubesats, small satellites originating from American universities, and seized the opportunity to participate in the first *Interplanetary CubeSat Workshop* in 2012 at M.I.T. in Boston. The first French CUBESAT, ROBUSTA, had just been launched, and I observed the timid arrival of this phenomenon in France, with the first forum organized in 2013 at the CNES pavilion during the 50<sup>th</sup> edition of the Paris Air Show.

Right away, a “message” shocked me: allegedly, a 3U CUBESAT (10 cm×10 cm×30 cm) could be built in 3 years for US\$ 1M. I found this message biased and irresponsible:

- Within 3 years, the CUBESAT must be launched and, if possible (as a secondary objective) it should be operational in orbit, the primary focus being to only showcase such projects!
- Cheap labor is implied, utilizing students whose university schedule in the USA allows intensive work on a specific project over 3 years.
- Furthermore, the “scientific case”, when it exists, is already feasible (i.e. high TRL) in CUBESAT format before this 3-year period.

The *NewSpace* marketing has also popularized “*Fly, Learn, Re-fly*”. It’s not surprising that sponsors were assured of a return on investment within 3 years. However, this overlooks technical risks and, worse, the psycho-social risks that such pressure imposes: we’ve seen exhaustion, burnouts, and even heart attacks among students and academic supervisors. One of my PhD students mentioned this risk for his project team in his peer-reviewed thesis paper (Dalbins et al. [2]), which was even documented in a film<sup>2</sup>. These breakdown risks, seen as shameful, became so pronounced during COVID-19 that an unexpected effect of the pandemic was to bring them out of taboo. However, I cannot endorse an environment where space engineering operates under such conditions, and along with others, I have criticized this pressure. The legend of “3 years” seems to have lost its allure today.

Nevertheless, it is certain that the CUBESAT format and the entire *NewSpace* paradigm can and must simplify methods. Let’s say they need to be modernized to enhance coherence and productivity for engineers.

Beware of another form of marketing, that of everything digital, with magnificent tools in catalog: UML modeling for generating code or documentation skeletons, SIMULINK instead of automatic control analysis, or the very modern “auto-code” from MATLAB to generate

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<sup>2</sup>“ESTCube saved my life” by Tero H. Savolainen, 2022, <https://vimeo.com/718959757>

flight software in C++. These tools (among others) are cited to illustrate the engineering approach that, instead, I would like to teach to “my” students and encourage engineers to adopt. Let’s be clear, all these tools are fantastic! But, in my opinion:

1. Functional analysis cannot be modeled in SysML/UML:
  - The primary purpose of functional analysis should be to distribute work within a team, choose interfaces for each, and allow controlled evolution.
  - In doing so, it must force the expression of needs, even before adopting a particular solution, and lead to prioritizing project requirements.
  - Furthermore, it should organize the validation, integration, and flight acceptance testing tasks downstream. Based on the “need”, it should include in-flight operations from the outset, following a philosophy of maximum autonomy to be controlled by a CubeSat team (although some companies offer this service at a high cost).
2. CubeSats are perceived by newcomers (students, engineers, or researchers) as akin to Lego<sup>3</sup>. Indeed, the excellent – but expensive – MATLAB offers SIMULINK to arrange modules into an automaton, clicked together in a library. Consider the example of modeling an attitude control system (also available off-the-shelf): I have seen models with three control loops (for each of the inertia wheels) and gyroscopic sensors, demonstrating rapid convergence of CubeSat pointing in the desired direction using a Kalman filter (and Monte Carlo simulations)... but forgetting the gyroscopic stiffness effect created by each wheel and their coupling! A 5-minute demonstration with a bicycle wheel (at CENSUS, we did this with a real CubeSat inertia wheel) is enough never to forget this pitfall of “off-ground” modeling and to remind that tests will always reveal forgotten effects.
3. Lastly, just as Monte Carlo simulations sometimes obviate the need for covariance analysis, advancements in onboard computers in NewSpace make auto-coding functions very enticing (similarly for AI-driven code generators), as they spare us from the arduous C++. However, beware the temptation to embed Python, known for its memory consumption and slowness. Space endeavors have always promoted resource efficiency, and flight failures could remind us if embedded software rules are neglected (e.g., no dynamic memory allocation, see online courses [3]). Personally, I emphasize the challenge of testing flight software, as evidenced by practices at Laboratory of Space Studies and Instrumentation in Astrophysics, Observatoire de Paris-PSL (LESIA) with the GERICO framework [4]. The Continuous Integration/Continuous Deployment (CI/CD) logic popularized in online services based on GIT/LINUX is a good inspiration.

My goal is to avoid over-quality in systems made less complex by NewSpace, but without escaping the minimum “documentary stack”, or compromising on the three golden rules of space: **testing, testing and testing**.

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<sup>3</sup>Plastic construction toys, designed in 1932, produced by THE LEGO GROUP, now part of everyday language.



The ambition to present “*NewSpace*”, or even just the state of the art in nanosatellite technologies<sup>1</sup>, would be excessive and a “Que sais-je?”<sup>2</sup> would not suffice<sup>3</sup>. In fact, there have already been so many introductions to the topic that one day we will need a peer-reviewed article to conduct a *semantic and historical review* to identify the common core and contradictions of all these attempts. Here, this presentation focuses on astrophysics and the reasons for the positioning I have chosen.

### 3.1 The CubeSat Standard, in the United States and Beyond

During the first “*Interplanetary CubeSats*” workshop organized at M.I.T. in Boston (2012), NASA finally announced a dedicated nanosatellite launch program: “finally”, because the CUBESAT standard (CalPoly and Stanford [6]) had spread like wildfire through American universities since the beginning of the previous decade. This standard involves adhering to a volume norm, in units of 10 cm × 10 cm × 10 cm, corresponding to the carrying capacity of a so-called Poly Picosatellite Orbital Deployer (P-POD) container which, rather than the satellite itself, is qualified for each launcher. This shift in qualification constraints lowered launch costs and stimulated new industrial chains (new containers, deployment stages, deployment mechanisms, famous COTS...). Prices further decreased later thanks to “wholesale rates” in launch services like those from SPACEX or ISRO, where slots are resold individually by “*brokers*”, such as the nanosatellite platform vendors themselves.

Even with this standard developed by top universities (CalPoly and Stanford), it still took over 10 years for NASA to give its endorsement. Even in 2023, there were resistances within NASA’s *Science Mission Directorate* regarding bandwidth allocation from the *Deep Space Network* for CUBESATS carried by ARTEMIS 1, to the detriment of conventional missions (Williams [7]). With more enthusiasm, JPL seized this momentum and, notably, two projects became emblematic for astrophysics: the twin MARCO-A and -B and ASTERIA, which immediately adopted a 6U volume (3 stacked rows of 2 units), for remarkably compact contents.

The twin MARCO-A and MARCO-B CUBESATS (*Mars Cube One*, Fig. 3.1, Cf. summary book by Kobayashi et al. [8]) were launched aboard the rocket that sent the INSIGHT probe to

<sup>1</sup>The 2024 edition of the *Small Spacecraft Technology State-of-the-Art*, [5], spans 441 pages, including, for example, 20 pages and 46 industrial references solely on avionics.

<sup>2</sup>A series published by Presses Universitaires de France (PUF) starting in 1941, notable for its diversity, low price, and the compactness of each book

<sup>3</sup>A book on the history of CUBESAT is being prepared by Prof. Bob Twiggs, Aaron Zucherman, Stephanie McPherson, and Clair Sapilewski



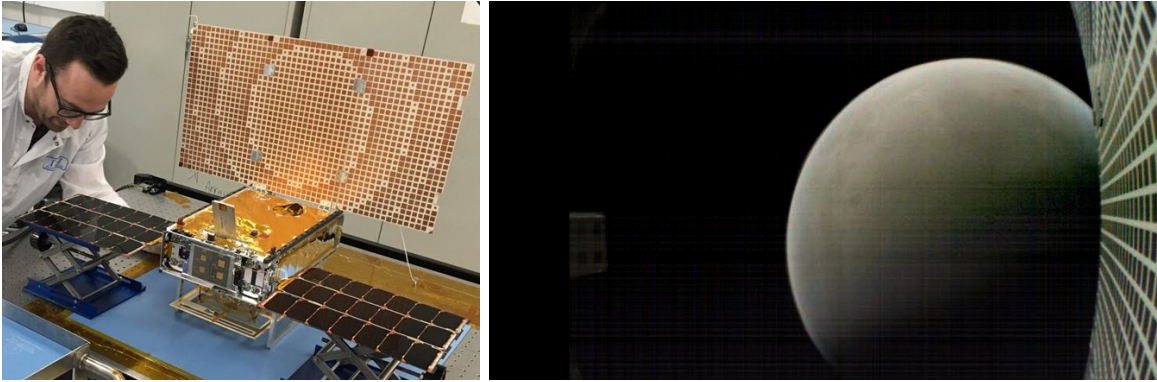


Figure 3.1: MARCO-A and -B (two units), JPL/NASA 6U CUBESAT, launched with the INSIGHT Mars probe. On the right, a photo taken by MARCO-B approaching Mars. (Credit: JPL/NASA)

Mars in 2018. After insertion into interplanetary transfer orbit, the three satellites were separated and continued their journeys independently. There were even two distinct operations teams, one for INSIGHT and another for the MARCO twins, working without interference. However, a powerful symbol, the two teams were united in the same control center on the day of INSIGHT’s arrival on Mars. They wore different polos to clearly indicate there were two distinct missions. The MARCO twins didn’t receive the “hurrah!” of a Mars landing, as they continued their interplanetary journey, but still enjoyed the general “*Ola*” of congratulations for the total success of both missions, as the data they relayed to Earth was successfully received live.

Indeed, the MARCO twins established the CUBESAT paradigm as valuable complements to traditional missions, even interplanetary ones: single objective, short cycle (but not 3 years!), compactness, and a new risk-price balance. The first principle of wisdom with CUBESATS is a single objective, which in this case was communication relay between INSIGHT and Earth during the EDL (*Entry, Descent, and Landing*) phase in Mars’ atmosphere on November 26, 2018, period! Other attempted operations (photographs of Mars, Phobos, and Deimos, atmospheric sounding by radio) were bonuses. The payload was a technology already mastered at JPL by 2014, since the precursor of the IRIS transponder *for* CubeSat in deep space was presented that year (Duncan et al. [9]). Even though the launch was initially planned for 2016, development thus took more than 3 years. As for the cost, it was around US\$ 18.5M for the twin satellites, including operations: hence, given the modest cost, one way to reduce risk was to create two satellites, a “hot redundancy” of the entire mission, which is another innovation of *NewSpace*. When scaled to a 3U format, this sets the new cost reference at US\$ 4.5M/3U, far from the US\$ 1M of a 3U student CUBESAT.

Another significant example from the same period (end of 2017) is the success of ASTERIA, also by JPL (Fig. 3.2). Let’s look at its genesis: the scientific case comes from M.I.T., with P.I. Sara Seager. I had the chance to see the first payload prototypes in 2012 in Boston, when the project was still “student”. It became professionalized under JPL’s leadership but clearly took more than 5 years and cost more than the imaginary reference of US\$ 2M (6U, Earth orbit). The design was made very compact, including optics initially featuring a commercial Reflex lens, and shielded for the space environment, which led to multiple project reviews (oral confirmations during conferences). The objective was technological, with photometric monitoring of stars (and possibly exoplanet transits) by stable pointing of about an arcsecond. The instrumental concept is to move the entire focal plane (an imager) to keep the target star’s image at the center through the lens. Despite a qualified space attitude control system (XACT by BLUE CANYON TECHNOLOGIES, a US\$ 100k COTS, the commercial “star” of the

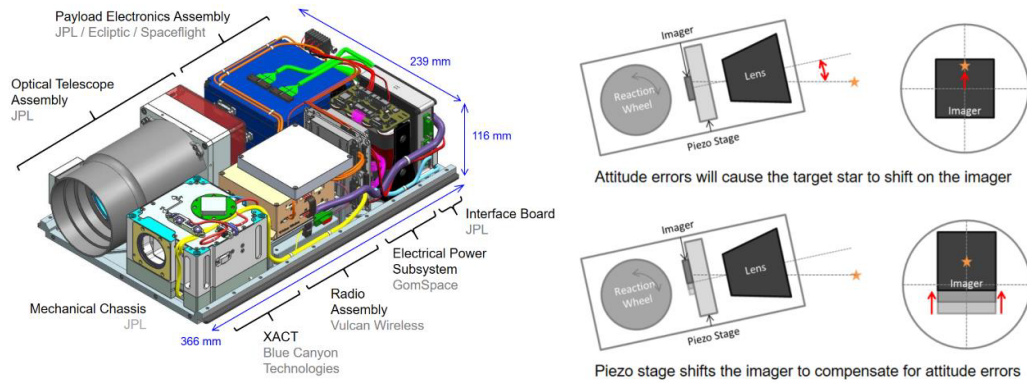


Figure 3.2: CAD view (left) and piezoelectric system for tracking the target image in the focal plane (right) of ASTERIA, a 6U CUBESAT by JPL/NASA, Smith et al. [10]

time), a wide field of view was planned for the imager to ensure the star’s presence in the field and then engage fine tracking. Moreover, a data rate of up to 1 Mbit/s was planned: the S-band was used, approximate pointing was sufficient thanks to two low-gain patch antennas on opposite faces.

In Europe, the von Karman Institute (Belgium) proposed the “QB50” program in 2011: initially planned as a constellation of 50 nanosatellites, the idea was to have each satellite built by a different university, delivering one of the three possible scientific payloads of the program (mass spectrometer, oxygen measurement, Langmuir probe, see Fig. 3.3) for integration. A single deployment was supposed to provide global coverage in low Earth orbit, to obtain a coherent network of plasma measurements over a long period. The approach, inspired by ProAm (Professional-Amateur) programs, aimed to strike a balance between scientific objectives and educational programs, allowing many universities to self-finance part of the costs. Ultimately, two separate deployments took place a month apart in 2017, totaling 36 nanosatellites. The program was a huge image success for the participating universities, the industry, and for the emergence of vocations. However, the scientific return did not meet expectations, confirming the difficulty of achieving professional quality solely through student programs. The European Commission published a very constructive review of the program<sup>4</sup>, including many lessons, notably the lack of tests due to lack of time which could have prevented observed failures. The total cost is stated to be €12M, but as it does not mention the financial contribution of the universities, it is difficult to use it as a reference.

ESA was involved as an expert in the QB50 program, led by the European Commission, which highlights its primarily political dimension. Facing the complexity of conventional space standards, ESA simplified its standards for a CUBESAT context as early as 2016. This resulted in two specific references, available online for free: product assurance and quality assurance requirements [11] and an ECSS standard [12], both targeting the goal of “demonstration” in orbit. A new ISO standard has also been available for purchase since 2017 (for only 216 CHF: ISO 19683:2017) and targets *NewSpace* with “*the minimum test requirements and test methods [...] while maintaining low cost and fast delivery*”. On the ESA side, particularly thanks to the continuous investment of Roger Walker over the past decade, now head of the ESA *CubeSat Systems Unit*, demonstrators have been initiated. Examples include: M-ARGO (P.M. Roger Walker, Fig. 3.4), under the optional GSTP (*General Support Technology Programme*), targeting deep space; OPS-SAT (P.I. Dave Evans) by and for the ESOC/ESA operations center to test embedded software (see the CENSUS “AbC” experiment

<sup>4</sup>Final Report Summary - QB50 (An international network of 50 CubeSats for multi-point, in-situ measurements in the lower thermosphere and re-entry research), <https://cordis.europa.eu/project/id/284427/reporting>



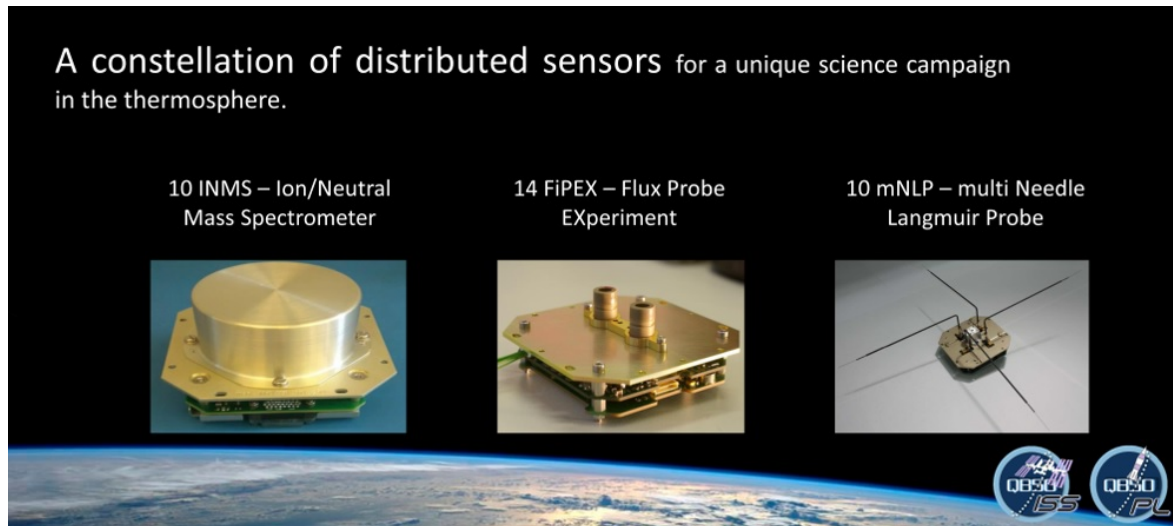


Figure 3.3: The three scientific payloads of the QB50 program in CUBESAT format (credit: QB50 Project, MSSL/UK, TU Dresden/Germany, University of Oslo/Norway).

in § 5.1.6); the future HERA mission with two 6U CubeSats: JUVENTAS, platform GOMSPACE Luxembourg-Denmark, and MILANI, platform TYVAK INT. Italy.

The Italian Space Agency (ASI) has achieved a particularly strategic positioning, now irrigating its laboratories and industry with *NewSpace* projects, both on the ground and in flight. Thus, the ESRIN/ESA facility near Rome includes the NEOCC (*Near-Earth Object Coordination Centre*) specializing in planetary defense, including asteroid exploration, where nanosatellites are a key component. This strong positioning has also been aided, according to my discussions with Italian colleagues, by a policy change in the 2010s calling for the return and permanent positions in Italy of many Italian astrophysicists who had expatriated to the best institutions in the world, due to lack of positions at home. Today, Italy is a leader in Europe in deep space nanosatellites: ARGOMOON on board Artemis 1 (08/2022), participation in M-ARGO/ESA to an asteroid and in LUMIO/ESA around the Moon, LICIA CUBE with DART/NASA to impact the Didymos asteroid (09/2022), MILANI accompanying HERA/ESA (10/2024), and more with propulsion and navigation technologies, notably. For example, in the CENSUS themes, the Polytechnic University of Milan (POLIMI) is in a very good position on autonomous navigation.

As student CubeSats proliferated worldwide, the failure rate dramatically increased (the *success* rate now, for all CubeSats combined, tends to increase, Villela et al. [13]). The low maturity of “technologies” was pointed out. I personally agree with the conclusions of the QB50 report to assert that the real culprit was, and remains, the lack of tests, inherent to space, due to lack of time, artificially imposed. If the level of testing expected for space had been met, the tests would have revealed overly optimistic assumptions about genuinely new technologies. One can thus regret the client’s naivety in paying the real price of “innovations”, while the industry enriched itself by imposing advance payments, even on public money, which was also a paradigm shift, without sharing the risk.

Another paradigm shift, but necessary, is for ground telecommunications and all operations activities. In S and X bands, MARCO-A/B already identified that current ground networks will not suffice to meet the trend and even less the scientific needs. This is true: S-band ground antennas target very rich markets (like IoT, *Internet of Things*) making them too expensive for astrophysics (e.g. KSAT/Norway or SSC/Sweden); institutional networks like DSN or ESTRACK or CNES prioritize conventional exploration missions. For UHF/VHF bands, amateur networks have grown tired of lending their frequency bands to

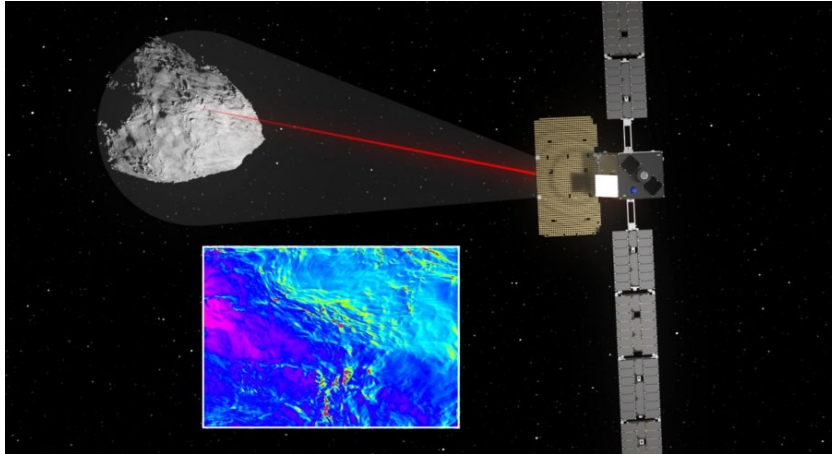


Figure 3.4: *Illustration of Lidar operations on M-ARGO (credit: ESA, Rui Braz).*

student projects for free, and in any case, the band is becoming too limited for the expected data rate and the frequency spectrum is starting to saturate.

It is worth mentioning the still timid emergence of asteroid mining applications where Luxembourg (and a few American companies) are trying to position themselves. To keep this introduction to nanosatellites relatively brief, despite the scale of the *NewSpace* phenomenon, I do not address Earth observation applications and the concepts of frequent revisits of nanosatellite constellations in Earth orbits. I also do not detail the industrial value chain that has developed in *NewSpace*, including in Europe, from sensors and actuators to complete platforms. However, the illustration in Figure 3.5 shows the European industrial ecosystem in 05/2023, where the (French) authors<sup>5</sup> proudly note that France is a leader in the number of companies (52 out of 220).

The previous examples show the emerging trends for astrophysics in the coming years: after plasma measurements, for which nanosatellites were immediately considered, the need for precursors and auxiliaries is increasing in all fields of astrophysics. The technologies that are missing to meet these needs are all targeting increased autonomy, particularly for deep space, which is the new frontier for the CUBESAT format. Technologies and infrastructures are slowly being put in place around the key word “autonomy” for nanosatellites in astrophysics, and especially:

- Continuous propulsion, along with autonomous navigation techniques<sup>6</sup>. Many players and numerous technologies are maturing; it remains to learn how to integrate them well, both in mission analysis tools and in attitude control systems and tests.
- Ground telecommunications, with minimalist operations concepts (onboard and on the ground), as UHF/VHF infrastructures will no longer be sufficient in the near future and existing ones are not adapted (to astrophysics).
- Even without seeking autonomy, the performance requirements for pointing and stability are higher than the state of the art. They impact the scientific observations themselves and navigation (propulsion and optical orbit determination). The rise of laser telecommunications (*lasercom*) to and from terrestrial orbits could serve as a springboard for astrophysics.

<sup>5</sup><https://toulouse-space-team.com/v2-carto-europe/>, 11/05/2023, Toulouse Space Team, consultants

<sup>6</sup>Riddle among aviators: What is the best navigation system? Answer: a large tank.

### 3.2. THE FRENCH NEWSpace (FOR ASTROPHYSICS)

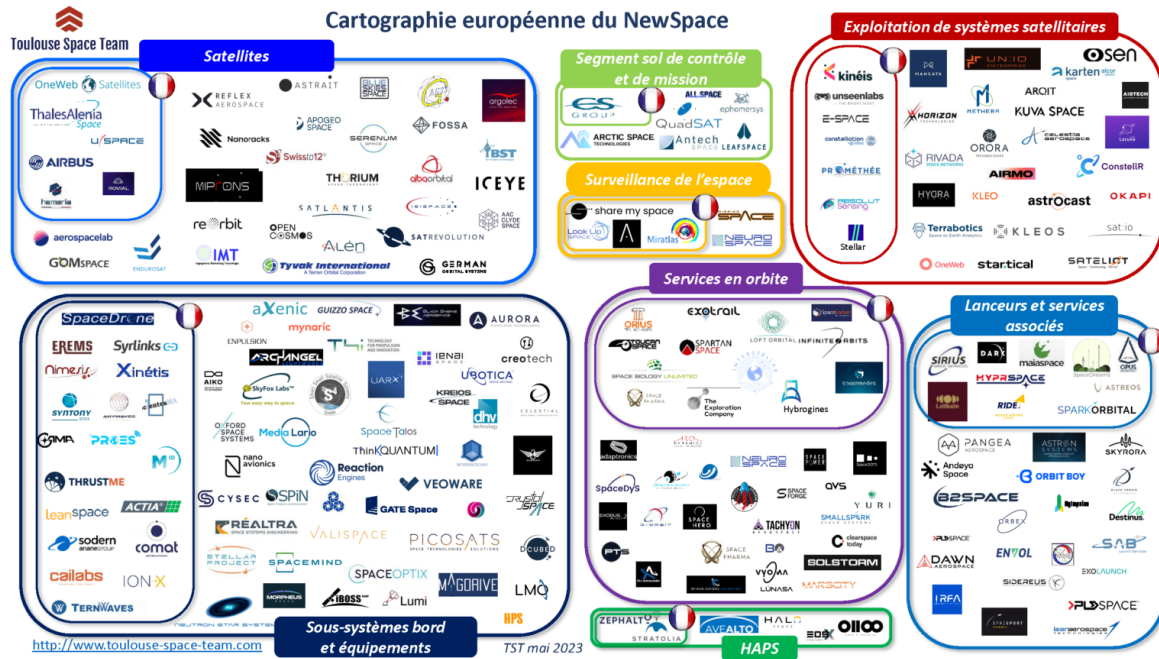


Figure 3.5: “Map of the European NewSpace” (Toulouse Space Team, 11/05/2023).

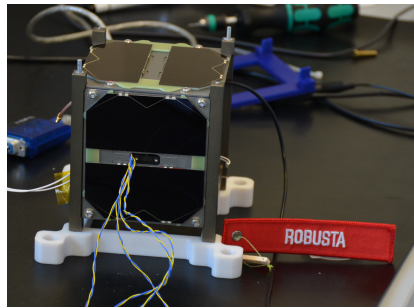


Figure 3.6: ROBUSTA-1B,  $10 \times 10 \times 10 \text{ cm}^3$ , radiation resistance test in space environment (photo NimesGEII, CC-BY-SA-4.0 license, CSUM, U. Montpellier-II).

### 3.2 The French NewSpace (for astrophysics)

In France, CNES initiated a nanosatellite program in 2013 strictly limited to student CUBE-SATS. Strangely, the academic vocation of the Observatoire de Paris-PSL, which awards Master’s and Doctorate degrees in its own name, was not recognized by this program, and the actions of C<sup>2</sup>ERES (now CENSUS) were ignored, despite co-funding other projects in this same program, for OGMS-SA (LISA/UPEC) and METEORIX (Institute of Celestial Mechanics and Ephemeris Calculation, Observatoire de Paris-PSL (IMCCE), Sorbonne University). This situation led us to choose, ultimately with happiness, a resolutely scientific positioning, whereas we had started without prejudging between science and education. It is difficult to judge the first phase of this CNES program because, to our knowledge, no economic and educational assessment has been published. Yet, its probable amount of €4M over 2012-2019 would justify it, estimated by considering an announced support of 50%, i.e. about €300-400k, for the twelve initially recruited projects (from 1U to 3U).

The continuation of this program, renamed *Nanolab Academy*, maintains these same educational objectives. The program published a “Normative Guide for the development of student nanosatellite projects” in 2021, [14], drawing on the technical lessons from the first

9 years. This echoes the ESA’s 2016 initiative to simplify conventional space in favor of *NewSpace*.

The technical framework of *Nanolab Academy* is to favor a platform that miniaturizes conventional space with a core system designed around a “hypervisor”. This approach is undeniably robust and has a strong heritage. However, it is expensive compared to the competition and too complex without an expert in these architectures for integration and testing. It would result in a loss of control for a scientific client and would impose costly subcontracting, including in operations. It would not change the paradigm and would expect the scientific laboratory to limit itself to a payload, without designing the entire mission, then deliver it to an external integrator and have it operated by an agency (or a company). But beware, European competitors also have a heritage and are already opening French subsidiaries to capture the institutional market, thus directly threatening the economic viability of the hypervisor architecture: ARGOTEC and TYVAK in Italy, ISISPACE in the Netherlands, NANOAVIONICS in Lithuania and announced in France, GOMSPACE in Denmark and now in France. Conversely, the Van Allen Foundation, linked to the University Space Center of Montpellier (CSUM, University of Montpellier), bridges the gap between academia and industry around a decentralized system architecture, robust by its simplicity, and a strong theme on radiation hardening: the foundation was created in 2012 following the launch of the CUBESAT ROBUSTA-1A (P.I. Laurent Dusseau), the first French nanosatellite. Its successor 1B is shown in figure 3.6.

CNES, in its mission to support French innovation, has resolutely helped the emergence of industrial players, as evidenced by figure 3.5. For astrophysics, players like SODERN will be critical suppliers, and in the near future, we will need to monitor the sustained effort for nanosatellite propulsion: THRUSTME and EXOTRIL, although the latter has repositioned itself on “SmallSats”, a category superior to CUBESATS. However, an opportunity for collaboration exists between *Nanolab Academy* and CENSUS at the ground segments level, as it is the only CNES entity to date that is interested in the needs of nanosatellites (confirmed in 2024, during technical meetings with the CNES department in charge of Telecom applications, ground stations, and alert systems).

On the scientific side, however, it was only in 2015 and at our insistence (LabEx ESEP and spatial pole C<sup>2</sup>ERES, see Chap.6) that nanosatellites were given a voice at CNES. Several projects were then supported by some modest funding. Above all, the experts from PASO/CNES, the Plateau for Orbital Systems Analysis, were able to work with us and played an important role in promoting nanosatellites within the agency. Among the very first scientific projects reviewed by CNES were BIRDY and NOIRE, detailed here.

In space laboratories, researchers and engineers quickly expressed themselves *for* or *against* the CUBESAT format, the former judging that it would lead to new observational concepts, the latter that the size would intrinsically limit performance. All agreed on the need to realize these small satellites with the same quality requirements as their predecessors, i.e. with professionals in the project team. However, the absence of funding other than educational did not allow the mobilization of permanent staff on these projects, which have therefore progressed laboriously to date.

In 2023, a decision was made by Coralie Neiner (LESIA, director of CENSUS) to create a CNRS research federation dedicated to scientific nanosatellites, initially limited to the Paris region, with a view to expanding. The first goal is to identify and express the common needs of the community. In 2024, a contribution from the federation to the joint CNES-INSU prospective workshop is made, calling for a “ticket-office” at CNES, dedicated to scientific *NewSpace*. Indeed, the collegial opinion is that *NewSpace* is essential for scientists but far too fragile in France compared to the opportunities of conventional space instruments. The federation estimates that a multi-annual budget averaging €3M/year would be effective, both

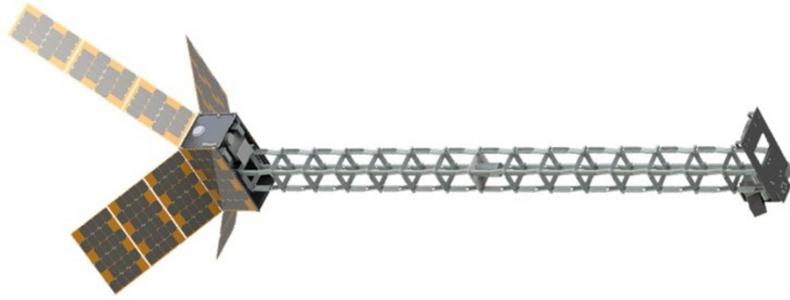


Figure 3.7: CUBESAT 16U NANOMAGSAT ( $22 \times 22 \times 44 \text{ cm}^3$ , deployable 3 m arm) for space weather (Open Cosmos & NanoMagSat consortium, ESA Standard license).

technically and politically.

The contrast is striking in France between the emergence of a French *NewSpace* economic value chain and the absence of science, especially astrophysics. This seems to illustrate the ideology of “innovation”, immediacy, and utilitarianism, which unfolds to the detriment of medium-term Research and Technology, as opposed to “innovation” (R&T). With socio-economic expertise, this hypothesis should be evaluated in light of the American or Italian situation. If confirmed, it would then overlook that in France, astronomy is a discipline with major political influence and that an astrophysical *NewSpace* is an opportunity to multiply this influence, with the national public and international partners.

Before detailing my actions over the past twelve years, I make the perhaps severe observation that France has missed the nanosatellite astrophysics boom, while the United States and Italy are reaping significant political success. In 2024, CNES appears ready to contribute to ESA nanosatellites, judging by the selection of NANOMAGSAT (P.I. Gauthier Hulot, IPGP, Fig. 3.7), a constellation of three identical CubeSats for the study of the Earth’s magnetic field dynamics, under the Earth Observation program<sup>7</sup>, for which PASO/CNES and R&T funding have been very helpful.

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<sup>7</sup>[Click here] ESA News from 21/02/2024:  
[www.esa.int/Applications/Observing\\_the\\_Earth/FutureEO/NanoMagSat\\_and\\_Tango\\_Scout\\_missions\\_get\\_go-ahead](http://www.esa.int/Applications/Observing_the_Earth/FutureEO/NanoMagSat_and_Tango_Scout_missions_get_go-ahead)



At CENSUS, the development of the support ecosystem for astrophysics nanosatellites happened without any pre-determined decisions. The thought process evolved as the need to secure projects arose. These projects, presented at CENSUS during the annual calls for proposals (initially from LabEx ESEP, see Chap. 5), are the true initiators of the reflections carried in this manuscript. Their great diversity since 2013 has highlighted needs that are either “pioneering” (BIRDY-T) or “recurring”. I have generalized what seemed necessary and feasible within CENSUS, leaving the specific or beyond-our-means tasks to the projects.

#### 4.1 Birdy-T: genesis and repositioning

This first nanosatellite project was a precursor in many ways. I was contacted in early 2013, through my connections at the Mars Society, to suggest and support a thesis project for a Martian CUBESAT. The doctoral student was Jordan Vannitsen, a French student at National Cheng Kung University, Tainan, Taiwan (NCKU). A relationship quickly developed between the LabEx ESEP, which I had just joined, and the aerospace engineering department of NCKU led by Professor Miao, J. Vannitsen’s thesis director, co-supervised by Dr. Kaithy Wang. We quickly oriented the project towards an idea by Ludwig Klein of LESIA for a space weather CUBESAT during an autonomous cruise from Earth to Mars:

- The payload would adopt the concept of the “RAD” instrument, a directional energetic particle detector developed by Hassler [15] at Southwest Research Institute (SwRI), *Instrumentation & Space Research Division* in Boulder (CO/USA), for NASA’s MSL-CURIOSITY rover. Although its operation was not planned during the cruise, it proved possible and informative during two *Solar Particle Events* (SPE);
- A CUBESAT on a Hohmann trajectory would allow observations from Earth, the CUBESAT, and Mars of the same SPE propagating through the solar system along spirals, thus demonstrating and quantifying the so-called “Hohmann-Parker” effect (Fig. 4.1);
- An autonomous interplanetary navigation function would maintain the CUBESAT on its pre-calculated reference trajectory, so as to retrieve its data during its Mars flyby via an already operational orbiter;
- The CUBESAT would include propulsion for a delta-V budget of 80 m/s, demonstrating a liquid propellant-based technology (see below) proposed by veteran propulsion engineers.

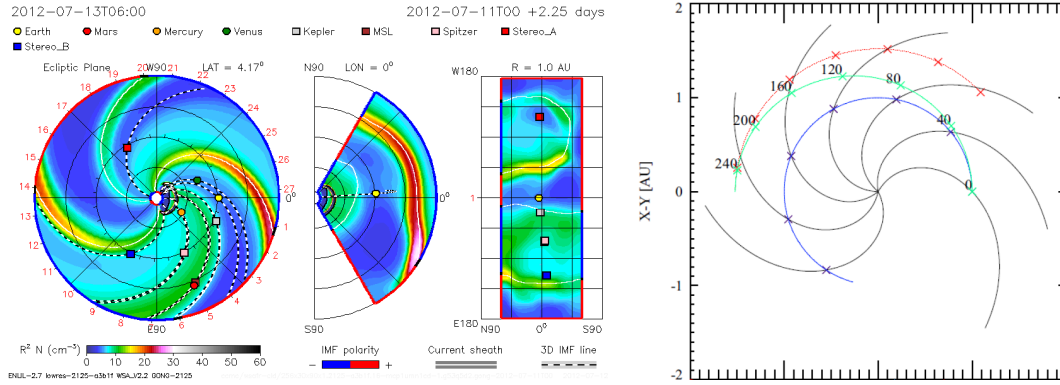


Figure 4.1: *Propagation of solar wind. On the left: real-time monitoring by NASA/GSFC. On the right (Posner et al. [16]): Parker spirals for a given energy level (black), connecting the orbits of Earth (blue), Mars (red), and a probe on a Hohmann trajectory (green). The crosses show the successive positions on the indicated dates (days) of Earth, the probe, and Mars.*

I served as project manager and coordinator between France and Taiwan, where many Taiwanese students were involved at the Master’s level and locally supervised by J. Vannitsen. On my side, I supervised French student teams from the OSAE Master’s program at the Paris Observatory or from various engineering schools, particularly from CENTRALE LILLE, for a proposed mechanical structure for the CUBESAT. At that time, there were still few COTS, and it was tempting to develop everything in-house, even though the goal of this particular module was educational and promotional (a presentation by the Lille team was given at the Mars Society France). This module was pushed to fabrication and a vibration testing session was reserved: students came with their prototype to install it in a “P-POD” test container, intended to hold a CUBESAT for launch from a rocket. But the prototype could not fit into the P-POD due to not meeting the strict mechanical tolerances of the CUBESAT standard! The exercise did not lose its educational value; on the contrary, it allowed me to illustrate the importance of early testing at all levels. The same mishap was reported as common in the European Commission report on QB50<sup>1</sup>.

The test P-POD, capable of receiving a 3U CUBESAT (or “Test-POD”), was a realization by NCKU in two copies, one of which was given to us. Two mechanical interfaces were developed to install it either on the vibration test equipment of colleagues in Paris area or on the SimEnOm thermal vacuum chamber at LESIA, thus providing a CUBESAT interface for thermal vacuum cycling. Later, I also had a Test-POD 6U purchased for CENSUS.

In addition to J. Vannitsen’s thesis in Taiwan on a measurement concept for BIRDY, two main studies were conducted in France:

- a thesis on the coupling between continuous propulsion and attitude control for nanosatellites, by Quinsac [17] under the supervision of Prof. Benoît Mosser and co-supervised by Christophe Koppel and myself, defended in 2019;
- my own thesis on an optical navigation algorithm in interplanetary space (Segret [18]), still under the supervision of B. Mosser, also defended in 2019.

G. Quinsac’s thesis demonstrated that the imprecision and instability of available attitude control systems in *NewSpace* led to excessive optimism for propulsion solutions. More deeply, the state of the art showed that the performance criteria traditionally used for attitude control and propulsion were no longer sufficient for nanosatellites: careful consideration of pointing or centering inaccuracies should lead (which is generally not done) to doubling or

<sup>1</sup>Cf. Final Report Summary - QB50, *infra*

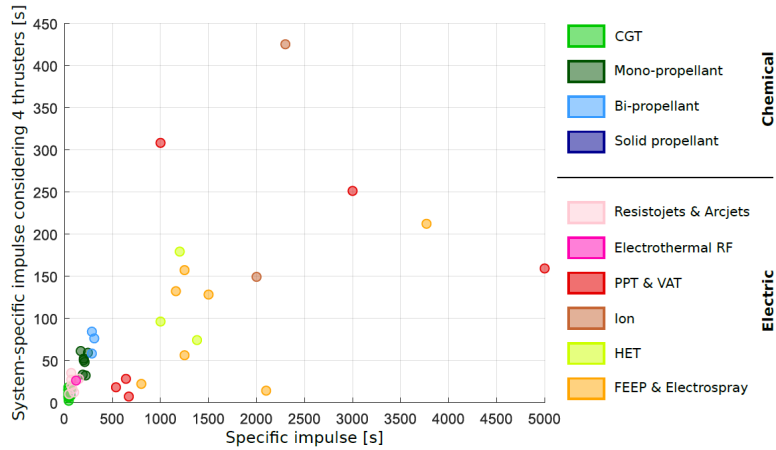


Figure 4.2: *System-specific impulse  $I_{ssp}$  as a function of specific impulse  $I_{sp}$  for several propulsion solution families, considering the use of 4 thrusters in sequence. Excerpt from Quinsac [17].*

even quadrupling the initially planned delta-V budget for maneuvers such as deorbiting from a low orbit. A new indicator replacing the famous specific impulse  $I_{sp}$  was taken from Erichsen [19] and was complemented as a “system-specific impulse”,  $I_{ssp}$ , redistributing propulsion solutions based on usage, as shown, for example, in Figure 4.2: a correspondence between  $I_{sp}$  and its translation to  $I_{ssp}$  should show a clear regression line, but instead, performances are completely scattered when transitioning from one to the other.

This thesis presented an original propulsion technology, Liquid micro-Pulsed Plasma Thruster ( $L\mu$ PPT), using a liquid propellant derived from Teflon. The technology was developed by Serge Barral (e.g. [20, 21]). It was promoted in France by Christophe Koppel, co-supervisor of the thesis with me, responsible at SNECMA (now SAFRAN) for the propulsion of the Earth-Moon SMART-1/ESA probe (2003 to 2006). However, our LESIA laboratory had already supported, but without follow-up, a Hall effect propulsion technology for nano-satellites (e.g. [22]), developed by Prof. Marcel Guyot (Univ. Versailles Saint Quentin) and Prof. Michel Dudeck (Univ. Pierre et Marie Curie), a technology that would give rise to the company EXOTRAIL. LESIA therefore refused to support the  $L\mu$ PPT propulsion for the BIRDY project, and it was not pursued further.

In my own thesis, I proposed a *Vision-Based Navigation* (VBN) solution for autonomous orbit determination in interplanetary cruise: it combines optical measurements of foreground objects against known stars and a “UKF” (*Unscented Kalman Filter*) estimator. This estimator proves more stable than the well-known “EKF” (*Extended Kalman Filter*) in cases of strong trigonometric evolutions (such as near Mars or an asteroid). It also presents a strong potential for adaptation to proximity operations and data fusion (typically combining optical and radio-science, Segret et al. [23]), which would become the new context for BIRDY. The complexity of the UKF ultimately proved manageable, despite a delicate but documented mathematical operation involving finding a square root for a matrix (Sadeghi [24]). The cruise performance reached, according to simulations, an orbit reconstruction accuracy of 30 km at  $3\sigma$ , **provided** that, in particular, an optical accuracy of 0.2 arcsec is achieved, representing a significant improvement over the state of the art, which we will revisit shortly. This thesis also introduced a modeling approach that reinjects simulation results into the satellite’s mission profile, a method I later developed under the name “MBSE”.

Incidentally, these two theses required the development of some space dynamics tools that formed the initial building blocks of the open-source software suite DOCKS, which will be presented in more detail in section 5.1.

However, a weakness of the project at that time was the lack of strong P.I. leadership from



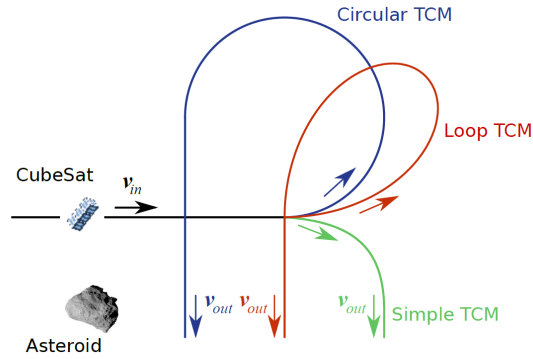


Figure 4.3: “TCM Loop” designed for proximity operations (Segret & Quinsac).

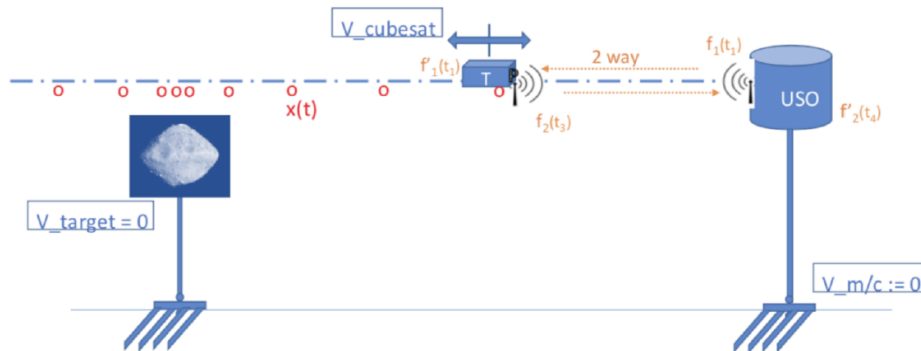


Figure 4.4: Ground demonstration: a trolley ( $T$ ) performs straight sections simulating distance and speed of an asteroid flyby during radio-science measurements from a fixed station ( $USO$ ). Hestroffer et al.

the space weather community to lead this Franco-Taiwanese project. Starting in 2018, the concept of an autonomous CUBESAT for deep space was taken up by Daniel Hestroffer to perform radio-science measurements near an asteroid. Under his initiative, BIRDY evolved into BIRDY-T, an “off-the-shelf” mission: it is considered either as a companion of a mothership mission for an asteroid rendezvous or for a single flyby for early reconnaissance of a potentially hazardous asteroid (PHA). The theses of G. Quinsac and myself were extended to this additional scientific case to address “proximity operations”. At that time, G. Quinsac and I also conceived a “TCM Loop” (Fig. 4.3), an autonomous maneuver for asteroid proximity, both tolerant, secure, and relatively simple, defined with a “rose window” parameterization, well suited for continuous propulsion:

$$\overrightarrow{OM} = R \sin 2\theta \begin{pmatrix} \cos \theta \\ \sin \theta \end{pmatrix}$$

When we wanted to publish a summary of the BIRDY orbit determination technique (ultimately published outside *peer-review*, [25]), it was heavily criticized. We indeed made an assumption beyond the state of the art for optical precision at  $\sigma_{\text{out}} = 0.2$  arcsec. However,

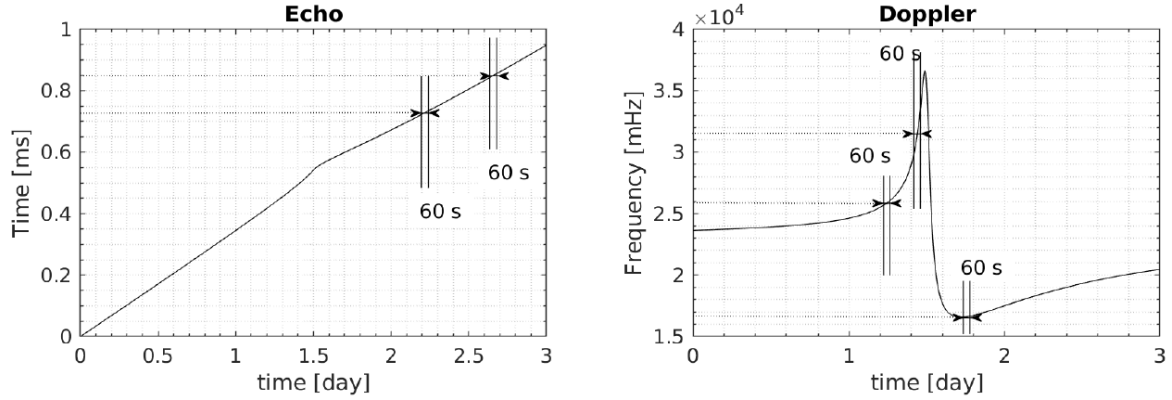


Figure 4.5: *Ground demonstration: the flyby trajectory is simulated (over several days) and then sampled into multiple segments (minutes) to be simulated by the trolley.*

this assumption is based on a realistic onboard preprocessing that should rapidly improve a raw precision of  $\sigma_{\text{in}} = 10$  arcsec if enough stars are recognized in the field:

$$\sigma_{\text{out}} \sim \frac{\sigma_{\text{in}}}{\sqrt{n^*}} \cdot \left( \frac{\sigma_{\text{in}}}{d} \right), \quad (4.1)$$

where  $n^*$  is the number of stars and  $d$  is the standard deviation of their inter-distances (i.e., their dispersal in the field). This other technology, later named “AbC”, was only presented but not yet developed, so reviewers remained skeptical that we could rely on such precision. Therefore, I initiated the development of AbC, which I specified (Segret et al. [26]) and then prototyped: it will be discussed in section 5.1.6.

BIRDY-T is currently in the ground demonstration phase of the radio-science measurement concept. A setup consisting of a {fixed station; trolley} is meant to simulate an asteroid flyby trajectory where acceleration is very low and collect radio-science measurements in the S-band. This set of measurements will serve as a basis to demonstrate that it is possible to test the technique’s performance on the ground and, ultimately, to reconstruct a trajectory that will constrain the asteroid’s mass to better than 10%. The ground experimentation is a project in its own right: not only does it require creating an S-band transponder and integrating the components, which is an investment of over 100 k€, but it also involves translating a space trajectory of several tens of kilometers over multiple days into a multitude of small straight segments on the ground of less than 500 m each and lasting a few minutes (Fig. 4.4 and 4.5).

#### *Summary for BIRDY-T*

It is difficult to predict the future of BIRDY-T, particularly whether it will fly. But BIRDY-T has already been significant for establishing an R&T dynamic within CENSUS. To date, the project has been the subject of three theses, has served as a topic for dozens of French and foreign Master’s and pre-doctoral students (PSL-ITI program of 2014); statistics on ResearchGate (which primarily concern BIRDY-T, but also include a substantial portion for NOIRE, Sec. 4.2) report over 80 citations and 4200 views; the open-source DOCKS suite has been initiated for rapid prototyping of mission profiles; the foundations of my future MBSE approach have been laid; a long-term collaboration has been established with the Luxembourg startup ODYSSEUS SPACE<sup>2</sup> created by Jordan Vannitsen with Marco Agnan and Julien Hennequinn; the AbC algorithm has been initiated with, recently, a few initial flights on the ESA OPS-SAT satellite (Cf. § 5.1.6); the feasibility of artificial intelligence

<sup>2</sup><https://www.odysseus.space>, 23/04/2024

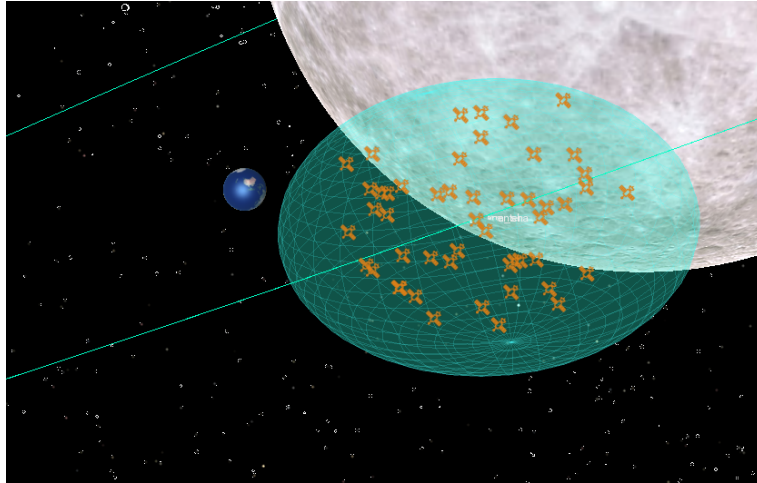


Figure 4.6: *NOIRE*, concept of a lunar orbit radio astronomy observatory consisting of 50 nanosatellites in swarm. Credit: E. Rouillé

for orbit determination is being studied by the German company D-FINE GMBH; and the adaptation of a radio-science technique to nanosat scale is underway.

## 4.2 NOIRE: Swarm for Low-Frequency Radio Astronomy

In 2014, I accompanied Baptiste Cecconi from LESIA / Observatoire de Paris-PSL to a workshop in the Netherlands to discuss an idea involving a swarm of nanosatellites. The goal was to explore the adaptation of LOFAR (*Low Frequency Array*, van Haarlem, M. P. et al. [27]), a ground-based radio interferometry observatory spread across several European countries, to a space-based application. This idea led to the study of “NOIRE”, supported by the PASO team<sup>3</sup> at CNES and led by B. Cecconi, for a lunar orbit observatory composed of around fifty nanosatellites in a swarm configuration (Fig. 4.6). Due to the ionospheric cutoff, which prevents ground-based observations below 10 MHz, this configuration offers numerous advantages:

- Complete sky imaging or targeted zone observations at chosen frequencies, addressing various scientific cases from planetary science to cosmology (examples below);
- Swarm operations require minimal orbit maintenance and provide multiple baselines ranging from 10 to 100 km in length and in all orientations;
- The lunar orbit allows alternating between shielding from terrestrial or solar emissions and observing the entire terrestrial environment;
- The number of nanosatellites allows for economical mass production and natural redundancy, potentially allowing for updates over time, even if some satellites must be specialized for distributing computational tasks (pre-processing by all, data reduction and transmission to Earth by some).

The study report from PASO/CNES concluded that there were no evident showstoppers, despite the project’s technical challenges. The first thesis dedicated to NOIRE was initiated under B. Cecconi’s supervision, with my co-supervision, undertaken by Erwan Rouillé since

<sup>3</sup>Plateau d’Architecture des Systèmes Orbitaux, responsible for sizing pre-projects selected by CNES (Centre National d’Études Spatiales)

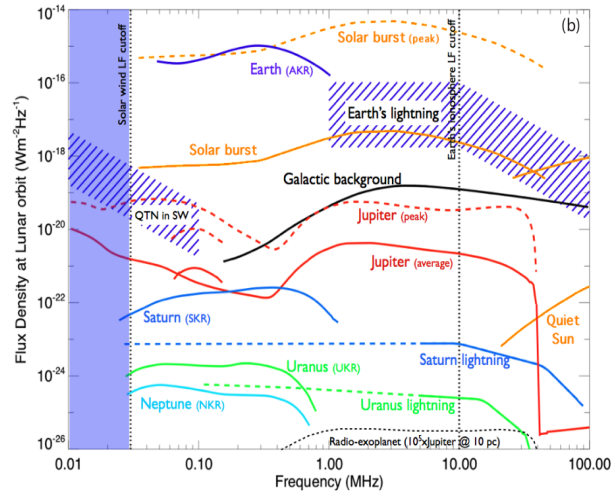


Figure 4.7: *Power densities of radio astronomical signatures from 10 kHz to 100 MHz (adapted from Zarka et al. [28], Zarka and Cecconi [29]).*

2022. Numerous scientific themes are accessible via NOIRE, with the primary challenge being to focus on the most impactful or “salesy” cases (*O tempora, o mores!*). This represents the first doctoral project for our student, aiming to establish the foundations of an instrumental simulator to support various scientific specifications.

The cosmological theme is particularly enticing but also the most complex: the goal would be to detect the signature of the cosmic dawn hydrogen line at extreme redshifts ( $Z \sim 1000$ ). This requires utmost sensitivity and the subtraction of all foreground signals, especially the unresolved galactic signal (Figure 4.7 shows relative powers). However, the cosmological case could benefit from support for decisive technological demonstrations, such as clock synchronization within a trio of nanosatellites or electromagnetic compatibility solutions.

Initial scientific case specifications lean towards solar physics and the rotation of giant planets: in the former case, imaging will enable precise characterization of energy transfer processes between particles ejected by the Sun and various components of the heliosphere (magnetic fields, solar wind, magnetospheres, etc.); in the latter case, shielded by the Moon from Earth, radio spectrum measurements of planets (Uranus, Neptune with poorly known rotation periods, and Jupiter for long-term monitoring) are feasible and would constrain the internal structure of ice giants, contributing to the broader understanding of gravitational moment distribution in the solar system.

These examples, spanning from cosmology to planetary science, illustrate a vast potential for observations that are otherwise impossible, addressing critical scientific questions that remain unanswered. Beyond the undeniable scientific interest of NOIRE, E. Rouillé’s thesis involves translating and quantifying scientific specifications into engineering constraints for a significant nanosatellite project. Particularly, I aim to identify possible simplifications compared to conventional space engineering approaches, favoring a *System Architecture and Design Technique (Structured Analysis and Design Technique (SADT))* modeling (I prefer to say “process maps”), which I use in all my projects and will detail in Section 5.2. While it may be premature for a full *Model-Based Systems Engineering (MBSE)* approach, it is certainly desirable and feasible for each quantified scientific case.

## 4.3 Many other projects: identifying the “cases”

BIRDY-T had demonstrated, if there was still any need to prove it, that a scientific project requires a dedicated researcher to lead it and a good “scientific case”. Without this, the project will find neither support, collaborations, nor funding. The range of topics addressed by NOIRE also supports this rule, as the selection of concrete and quantifiable scientific objectives allows us to progress. For all the projects I will support thereafter, I will insist on identifying the scientific cases in detail, which will also be essential for prioritizing technical specifications. The sections below do not follow a chronological order, as many projects were conducted in parallel, with the aim in chapter 5 to outline the development axes I have chosen for CENSUS.

### 4.3.1 PICSAT, the Honorable First

In January 2018, France’s first scientific CUBESAT was launched. This achievement is due to the impressive energy of a small team from LESIA, led by Sylvestre Lacour and Vincent Lapeyrere. The lessons that PICSAT has left us are constantly present in my advice to other projects, particularly the need for strict control of *NewSpace* suppliers and the impossibility of skipping tests, even when they are not possible (sic). My contribution to PICSAT was quite minimal (reviewer for LabEx ESEP, which was a co-funder), but I owe a lot to it for the decisive programmatic success it represented in the start-up of CENSUS and for its feedback, hence this section.

The scientific objective was to continuously monitor the star Beta-Pictoris through photometry, during a period when a transit of its planet *Beta-Pictoris b* across the star was estimated to be probable. This goal was linked to demonstrating a technology for injecting light into an optical fiber by actively tracking the light spot in the focal plane: the “mono-pixel” sensor was therefore moved by piezoelectric actuators controlled at 100 Hz (the CUBESAT ASTERIA, see infra, also adopted this strategy where the entire imager was mobile in the focal plane). The entire development, from design to delivery for launch, took less than 4 years, from 2014 to 2017 (Fig. 4.8). Telemetry data showed that the onboard technology worked as expected. However, a failure of the pointing system (COTS, provided by HYPERION/N.L. based on a design from BERLIN SPACE TECHNOLOGIES AG) prevented the satellite from stabilizing, and the star was not observed. PICSAT ceased operation after 10 weeks, during a passage through the South Atlantic Anomaly, while a software update was in progress and a solar event had just occurred. For the record, PICSAT resumed transmitting on 21/06/2022 (accidental wake-up) until 10/05/2023 before re-entering the atmosphere. Despite several successful TC/TM exchanges, it was not possible to diagnose the satellite’s initial failure.

The lessons from PICSAT for myself and for CENSUS can be summarized as follows:

- The *NewSpace* marketing claim of building a CUBESAT in 3 years is a guilty lie (less heard nowadays), which seduces funders but leads the project team to take risks (sometimes human) and make technical shortcuts, particularly at the testing phase;
- *NewSpace* suppliers must remain controlled by the project team, even if it means inventing new purchasing techniques that would require sharing risks when flight heritage is not proven, which was the case here for the attitude control system provided as COTS.
- Public procurement methods are not at all suited to the dynamics of *NewSpace*, which shifts all contractual risk onto the team; these methods need to be revisited;
- The only shortcuts that should not be taken are on testing (more important than operational performance, which should include margins); tests must cover all “functions”



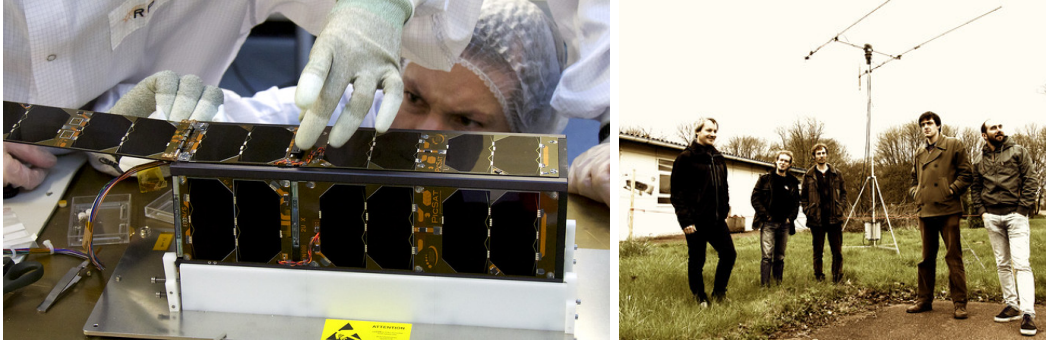


Figure 4.8: *The CUBESAT PICSAT, 3U format, during integration. The PICSAT team (left to right: Vincent Lapeyrere, Lester David, Antoine Cruzier, Mathias Nowak, Sylvestre Lacour; absent: Guillaume Schworer, Maarten Roos) in front of the UHF/VHF ground station from 2018, which will be consolidated by CENSUS. Credit: PICSAT team.*

and include a strict contractual acceptance on the ground for all COTS purchased; attitude (or even orbit) control is intrinsically difficult to test, even more so in a black-box context with COTS, and it will be necessary to combine impulse response tests with simulations to “de-risk” as much as possible;

- The ground segment must be initiated and completed at the same time as the satellite with, in particular, a constant focus on simplicity of operations and still time for testing and training: the satellite should work “by default”, i.e., without needing commands and telemetry interpretation on-the-fly (as much as possible);
- Finally, as with the ground segment, data processing (*housekeeping* or scientific) must be prepared in parallel with the satellite to allow its ingestion into a *pipeline* from the start of operations and contribute at least to flight acceptance, and ideally to communicating the first scientific results to the public.

LabEx ESEP funded some equipment as well as the launch. At the end of the project, CENSUS recovered the UHF/VHF ground station and consolidated it (see Chap. 5). Lastly, it is worth mentioning that PICSAT was also a tremendous success in public communication, with a report on the news of FRANCE 3, national TV, and the involvement of the global amateur radio community, with over 100 people contributing to collecting PICSAT data. So, many thanks again to the PICSAT team.

### 4.3.2 CASSTOR, precursor to Pollux

With the CASSTOR project, we used my MBSE approach for the first time in interaction with CNES. It proved to be very effective in deeply addressing platform constraints.

CASSTOR is a technological and scientific demonstrator, led by Coralie Neiner from LESIA: it is intended to demonstrate the feasibility of an ultraviolet spectropolarimeter, a precursor to the Pollux instrument proposed by CNES as a French contribution to NASA’s HWO mission (formerly LUVOIR); it must also provide the first UV polarimetric observations of a selection of stars, giving access to their circumstellar environment. UV observations, thus from space, detect magnetic field tracers in the atmospheres of stars, rather than just on their surfaces as done in IR. This knowledge is the basis for the material transport laws in the vicinity of stars.

To demonstrate the feasibility of such measurements, each target must be pointed at and integrated for a sufficient time, with high stability and always the same orientation on the



Figure 4.9: *Summary under VTS of observations for each target, in rows: success (white), partial success (blue), failure (red). Credit: CASSTOR team.*

axis. It is also necessary to regularly observe “calibrators” (calibration stars). An obvious compromise arose between platform stability and the need for fine pointing at the instrumentation level. Another analysis quickly emerged: how to reconcile orbital movement with the need for long integrations of most targets? And, additionally, the usual considerations of power budgets and data volumes came into play.

For platform stability, the requirements were such (0.23 px pointing stability, or  $\sim 2$  arcsec) that no known platform met them, as the usual pointing performance is around  $0.1^\circ$  off-axis, nearly 200 times worse. A “fine-pointing stage” was therefore required in the instrument, to be coupled with the platform’s attitude control system. It is clear that the “astrophysical” need is not covered at all by commercial solutions which favor Nadir observations during the day. To meet the expected observation durations, experts at CNES generally provide their analysis in the form of duty-cycles (percentage of orbit time available for scientific observation), and then turn to the scientific team to ask if this is acceptable. However, this macroscopic analysis poorly adapted to the diversity of stellar targets considered, with the risk of concluding operational infeasibility. Regarding power and data volume needs, CNES also responds with acceptable duty-cycles (for the platform and ground). Again, the risk was falling into overly simplified schemes requiring excessive scientific arbitration: restricting the number of targets or underutilizing the orbit.

Instead of duty-cycles, we eventually discussed a strategy that allowed us to automatically establish an observation schedule, which was then compared to a complete mission profile (Fig. 4.9). CENSUS modeled the mission profile, with our engineers Rashika Jain and then Feliu Lacreu, whom I supervised: calculations for the orbit, pointings, accumulation of observations, data volume, operational time (power)... Based on these “models”, I led a concurrent engineering campaign with the project team (Nov.2021, and updated in 2023). In preparation for the campaign, we agreed that Vincent Lapeyrere, project manager, would design the planning model, while CENSUS would create models to check if the required observation conditions are met and, if so, count the successful observations. The goal of the campaign was to anticipate the main orbit and platform options that CNES would propose, for example due to Sun, Moon, and Earth limb avoidance angles. When hard points were raised and required adaptations, this approach allowed us to quickly update the observation strategy and show that the schedule could be adapted to maximize scientific needs.

It is useful to emphasize here the need for preparing a concurrent engineering campaign. As I have monitored the techniques used by CNES, ESA, and JPL at NASA, particularly during the SECESA conferences organized every two years by ESA (Cf. Chap. 6), I have been convinced to prepare the team in advance and choose some concrete objectives, adapted to the project's maturity. In this case, for a 2022 campaign over 5 consecutive days, I proposed to Coralie Neiner and Vincent Lapeyrere to target a fluid model architecture with an initial observation strategy, and a detailed analysis of the platform/instrument alternative for fine pointing. These planning and observation analysis models are the MBSE approach that will be developed in § 5.2: we do not simulate the instrument (which would take years), but the *expected* conditions for a successful observation. Thus, we set both the specifications for the scientific payload, the requirements to be met by the entire system (flight and ground), and the verification reference for these requirements (the mission profile).

For CENSUS's expertise, the CASSTOR project brought a lot:

- the demonstration that a so-called “MBSE” modeling is reactive and changes the nature of the dialogue with the space agency, and probably with any platform supplier;
- the full-scale experience of a concurrent engineering campaign prior to a CNES phase 0, thus at an intermediate maturity level, i.e., CML 4 towards CML 5 (the “CML” scale will be presented in chapter 5);
- the astrophysical requirements going beyond *NewSpace* performance, we will need to find the right way to interact with suppliers, knowing that our projects are a possible showcase for them, but not a market.

### 4.3.3 CURE: Ephemerides for ARIEL

Here is a project that could not come to fruition. However, the return on investment is far from negligible: it has indeed become the technical basis for developing our educational products in concurrent engineering. As I observed for BIRDY-T, a project without P.I.-ship has no future, and this one was proposed in 2017 by Vincent Coudé du Foresto from LESIA, who soon after became the director of LESIA. His availability for CURE thus declined, and similarly, he lacked human resources. The connections between the ARIEL project, an ESA mission in preparation, and BIRDY for asteroid exploration also revealed common relationships with the Tartu Observatory (Estonia), with which a long-term partnership was established on this occasion.

ARIEL is the future ESA M-class mission for IR spectroscopy of exoplanet atmospheres. The central idea of CURE is that ARIEL's observation planning is so dense and complex that an error in the transit date of a target (Cf. Fig. 4.10) would cost approximately the price of a CUBESAT project. Therefore, it was interesting to consider a CUBESAT whose objective would be to verify the transit dates to optimize ARIEL's planning. Indeed, the dates of exoplanets passing in front of their star are estimated with an error that increases the longer it has been since the last confirmed transit date. If CURE can update these dates with high precision, it saves on ARIEL's planning margins.

Of course, the issue is justified for ephemerides that can only be confirmed from space. The collected signal must be sufficient to *fit* a model of brightness drop based on the photometry achievable with a CUBESAT. An invited English PhD student for the occasion, Billy Edwards, handled this aspect. Under the coordination of Vincent Lapeyrere and with the mobilization of a team from the Tartu Observatory experienced with CUBESATs ESTCube-1 & -2, we organized a one-week concurrent engineering campaign in Meudon in April 2019, between two summer schools in Tartu (2018 and 2019) that exploited this scientific case. I was responsible for preparing an initial MBSE architecture and for leading the week in



### 4.3. MANY OTHER PROJECTS: IDENTIFYING THE “CASES”

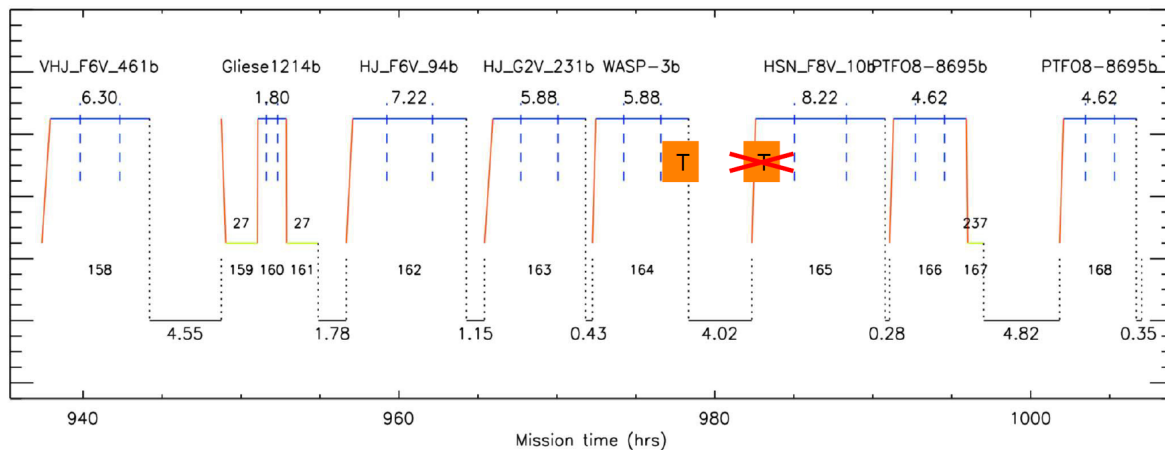


Figure 4.10: *Planning an observation by ARIEL, illustrated in the case of an exoplanet transit at a poorly estimated time. Credit: V. Coudé du Foresto*

Meudon. The campaign’s results identified two families of targets, for two different optical configurations (single-target PICSAT type or multi-target imager type) that could justify a mission profile. However, in conclusion, these families were deemed too limited compared to ARIEL’s target population of a thousand stars.

It should be noted that the need for ARIEL preparation has been well established since 2017: for targets that could be confirmed from the ground, a participatory science program called “ExoClock”<sup>4</sup> has been set up, with already 800 participants worldwide.

Due to its highly appreciated exoplanet theme, the CURE project has been an excellent support for introducing groups to concurrent engineering. I thus reformulated the scientific challenge to adapt it to a target audience of M2 to D1 students, and the engineering challenges for L2 to M2 students. Specifically, if PhD students are present, they should start from an SNR estimate that will determine the number of required observations for a list of exoplanets. If there are no PhD students, this number is directly provided in the table of exoplanets to observe. For engineering, depending on the participants’ levels, it is possible to include energy sizing, attitude control, or data volume. I have already led a few sessions based on this (Cf. §6.3).

Finally, the relationship with the Tartu Observatory has developed. It began with my meeting in 2018 with Andris Slavinskis, then a post-doc at NASA Ames, at the IEEE Aerospace conference in Big Sky (MT/USA) around interplanetary missions to asteroids. We found common scientific interests on ARIEL, with V. Coudé du Foresto on my side and Anna Aret at Tartu, and then funding from the Europlanet Society, suggested by its president Nigel Mason, also met in Tartu. The relationship continued with the co-supervision of PhD student Janis Dalbins (Cf. Chap. 5), who was already part of the team invited to Meudon for the CURE campaign. This project thus also illustrates how my networking activity (Chap. 6) fosters collaborations.

#### 4.3.4 TERACUBE: The Winds of Venus

While the Laboratory for the Study of Radiation and Matter in Astrophysics and Atmospheres, Observatoire de Paris-PSL (LERMA) had secured its selection for the Terahertz chain of the SWI instrument aboard the ESA’s JUICE probe, Jeanne Treuttel and her colleagues saw in the CUBESAT format a means of deploying this instrumentation for destinations other than Jupiter. With the support of Raphaël Moreno from LESIA in a P.I. role, they

<sup>4</sup><https://www.exoclock.space/>, visited 24/04/2024

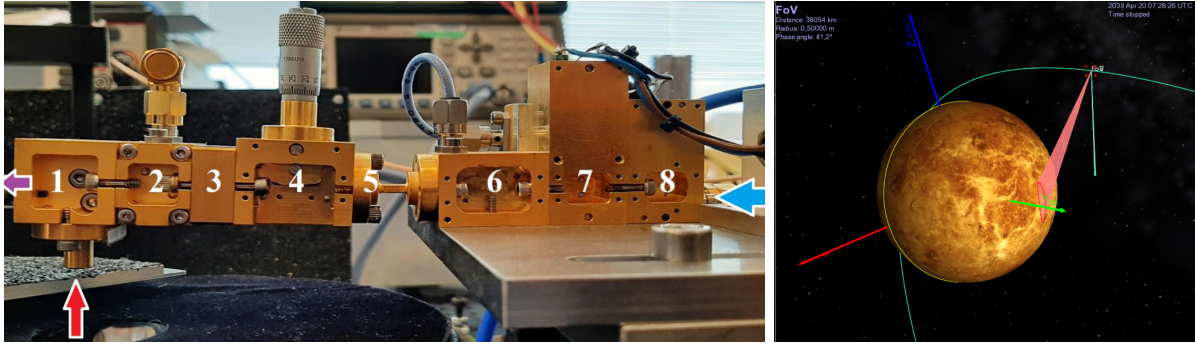


Figure 4.11: On the left, TERACUBE instrumentation: the signal to be observed at 600 GHz is injected from below into the mixer (1) with a reference signal at 300 GHz obtained through successive multiplications (2 to 8); the heterodyne signal from 1 to 10 GHz is collected on the left, amplified, and digitized (credit: J. Treuttel). On the right, an example of orbit and pointing for TERACUBE around Venus.

proposed the TERACUBE project (Fig. 4.11) starting in 2021 as a companion satellite to the armada heading towards Venus at the beginning of the next decade, particularly the ESA’s ENVISION probe. The spectrum between 300 and 600 GHz allows for the measurement of the abundance and movement of atmospheric tracers on Venus, at altitudes not covered by other planned missions, thereby completing the in-depth exploration of our nearest neighbor, which has been somewhat neglected until now.

CENSUS is primarily involved in the mission profile of TERACUBE. On one hand, there is the adaptation of a technology initially designed for Jupiter and revised for Venus by the thesis of Tomas Thuroscy (collaboration LERMA-IETR-C2N<sup>5</sup>), in a much more compact format and a priori in a much warmer environment (collaboration LERMA-LESIA). On the other hand, a strategy for observation needs to be developed, and once again the MBSE approach will be my answer to the advisory needs of TERACUBE. Engineer Feliu Lacreu, whom I supervised at CENSUS, provided trajectory profiles and modeling using VTS (free visualization software, see Chap. 5). Based on this, I proposed a pointing strategy involving continuous rotation of the CUBESAT on its orbit, thus at a low attitude control cost, alternately ensuring observation of the atmosphere at different latitudes and calibration with a cold source when facing the sky. CENSUS is responsible for geometric analyses (cuts, solar hours, zenithal angles, surface coverage, etc.). The advantage of the MBSE architecture is, of course, to set up these calculations and graphical representations to easily update them when new hypotheses are considered. The concurrent engineering techniques employed for TERACUBE, at CML maturity stages 2 to 3, focused on the “Manifesto” and the identification of “metrics”, steps which will be detailed in chapter 5.

#### 4.3.5 COSMOCAL: Calibration Target

I will conclude this detailed list with the COSMOCAL example (Ritacco et al. [30]), which differs from other projects in two ways: first, the payload is the observable rather than the observer, and secondly, it may ultimately not be a CUBESAT. Anyway, CENSUS’s first goal is to support PSL laboratories in exploring new options, without prejudging the most suitable format.

In this case, the project will allow the observation of the *polarization* of the cosmic microwave background. This information, in addition to temperature maps, is a signature of

<sup>5</sup>IETR: Institute of Electronics and Digital Technologies - UMR CNRS 6164, Rennes  
C2N: Center for Nanosciences and Nanotechnologies - UMR CNRS 9001, Saclay

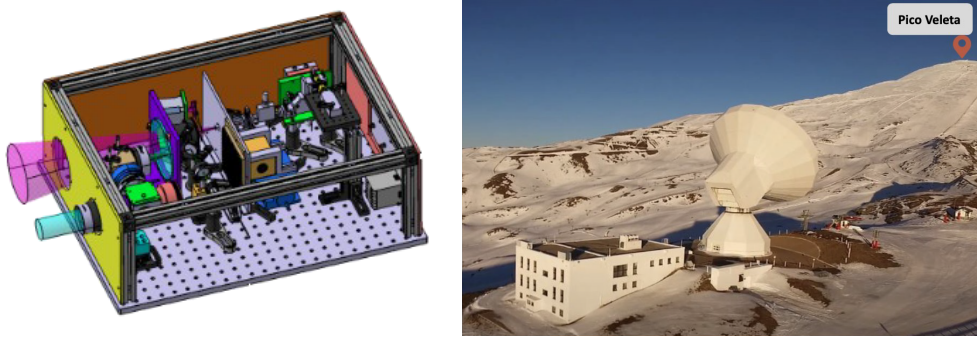


Figure 4.12: *Ground prototype of COSMOCAL: a 270 GHz source and a polarization grid illuminate, from Pico Veleta, the 30 m IRAM antenna located a few kilometers below.*

primordial ages that is still lacking and represents the next step in uncovering the quantum origin of the universe’s structures. The project is led by Prof. François Boulanger at École Normale Supérieure, PSL (ENS) with Dr. Alessia Ritacco at Tor Vergata University in Rome<sup>6</sup>.

COSMOCAL is intended to be a calibration source for large ground-based instruments, and possibly in space if the LITEBIRD mission is selected by ESA. Several frequencies are considered, around 90, 150, and 250 GHz. The challenge is to place the source far enough to obtain a plane wave while perfectly reproducing (within  $0.1^\circ$ ) the polarization angle of the emitted signal. My role in CENSUS for COSMOCAL has primarily been to advise on the range of possibilities with nanosatellites and the thermo-elastic issues in the space environment, during working meetings and preparation of funding requests. Through our industrial relationships, we also explored the option of placing COSMOCAL in geostationary orbit, which initially seemed too expensive to CNES but might turn out to be more economical than a complete nanosatellite development. However, we are leaning towards the “GEO” option: not only would low Earth orbit lead to too rapid tracking by large ground-based antennas and medium orbit would impose costly deorbiting constraints, but the attitude knowledge performance, even if  $0.1^\circ$  is modest, would still require precise telemetry dating and non-trivial ground operations.

#### 4.3.6 And many more

It is neither possible nor relevant to detail all the nanosatellite concepts that researchers have presented at CENSUS here. The reader will at least be convinced that their imagination knows no bounds when given opportunities to realize their ideas. I will mention a few collaborations that have been considered or initiated, for which I have been consulted and which have been meaningful for CENSUS:

- During the first Covid-19 lockdown, many students were “stuck” in their rooms with precarious internships in telework. I found myself supervising such an M2 intern to build a MBSE architecture for the CUBESAT he was studying. This intern, Lancelot Le Guern, later became the systems engineer of the young company GAMA, which we supported during some tests and which launched the first French solar sail in early 2023, on a 6U CUBESAT from NANOAVIONICS.
- SCION-X (INSPIRESat-6) is a Taiwanese CUBESAT led by Loren Chang from the Institute of Space Sciences at National Central University, Jhongli, Taiwan (NCU), in

<sup>6</sup>Dipartimento di Fisica, Università di Roma “Tor Vergata”, Roma, Italy

cooperation with NTU Singapore<sup>7</sup>. This collaboration was opened under the LabEx ESEP and I was invited to a Preliminary Design Review (PDR) for this air pollution monitoring project (WANG et al. [31]). Later, I presented the MBSE approach, which was very well received for its ability to structure the various studies within the team. I was then re-invited to Taiwan to introduce it to the local team (including two PhD students and Master's students). Unfortunately, the Covid crisis interrupted this relationship to this day, which was a missed opportunity.

- TUDSat is an Austrian-German student project<sup>8</sup> to test laser communication between Darmstadt (Germany) and Graz (Austria) via reflection on a target nanosatellite. Its project leader, Fabian Burger, whom I met at a conference, developed an MBSE architecture on my advice and with my initial support.
- OPS-SAT is a 3U CUBESAT built and operated by ESA/ESOC (Darmstadt), led by David Evans [32]. From 2020 to 2024, OPS-SAT was a space platform for testing embedded algorithms. I contacted the team following an *Open Source CubeSat Workshop*, and my “AbC” algorithm idea (initially developed for BIRDY-T) was selected and funded for its first flight tests. We then serendipitously identified an unexpected application to characterize the stability performance *of the platform* itself (see also §5.1.6).

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<sup>7</sup>Nanyang Technological University, Singapore

<sup>8</sup><https://tudsat.space/>, visited 28/04/2024



## The CENSUS ecosystem, space pole, expertise hub

There emerged topics on which I could naturally design original practices, especially at the beginning of projects, in phases 0/A. I also identified the need to go further and prepare for integration stages, including procurement and operations. I was less competent in these stages, so I chose to hire engineers. Their role was crucial in establishing an ecosystem that did not yet exist. Without claiming to be comprehensive, it already presents a robust and, hopefully, relevant vision.

### 5.1 Everything is a project

At CENSUS, “everything is a project” (paraphrasing the *Unix* world): those we support in various ways, but also those we conduct ourselves, that become our “assets”. Generally, these result from a need that arose for a nanosatellite project (often BIRDY-T) that deserves to be carried further to serve in other contexts, where the initial project cannot accompany them, with a view to securing its own funding. This goes against the *project-based funding* ideology, which claims that a team already overworked, given scarce funding, would still find resources to think about a *Business Plan* (especially since the *business* skills is at odds with astrophysics, absent from the hiring policies of lab’s institutional bodies and from the courses we offer).

I thus set up “internal projects” at CENSUS, based on the need to link phases 0/A (feasibility) to E (exploitation) of a nanosatellite’s life cycle, at the pace of the resources I could involve.

#### 5.1.1 PROMESS platform, mission profiles

**PROMESS**, “Mission Profiles and Space Sciences Education”, is CENSUS’s concurrent engineering platform. I designed and built it in 2016-2017, in collaboration with the *Unité de Formation et d’Enseignement, Observatoire de Paris-PSL (UFE)*. The PROMESS platform has 21 computer stations for UFE with their own Debian system, 7 of which are also equipped with a Windows system dedicated to CENSUS. A comfortable projection on 2 giant screens from any of the 7 machines, along with a quality audio system for remote participants, completes the equipment (Fig. 5.1). We therefore have a comfortable and very operational room.

But the most important thing is not, and never has been, in the equipment or the software (participants use our workstations as much as their own computers with their own specialized software). The important thing lies in the engineering method by which the campaigns are organized and conducted; this method is presented in §5.2.



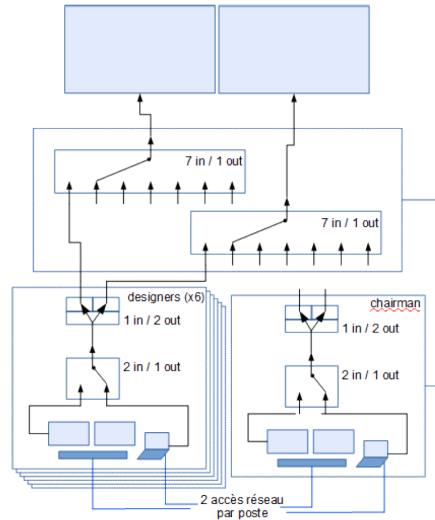


Figure 5.1: Video sharing between computer stations at the PROMESS platform.

### 5.1.2 DOCKS, rapid prototyping

**Design and Operations Cross-checking Services, CENSUS open-source software suite (DOCKS)**, Fig. 5.2, is currently coded in *python*<sup>1</sup> and is under the GNU GPL v2 license. Its use facilitates the prototyping of a mission profile, typically in phases 0/A, but also in preparation for phase E.

Several modules have already been developed: a flexible-step trajectory propagator with customizable perturbation models, quaternion calculations according to proposed pointing strategies, intervisibility event calculations (eclipses, ground station visibilities, occultations between objects), on-board energy modeling and estimation<sup>2</sup>, a remote DOCKS server to run calculations on a CENSUS machine via *drop & collect*, which avoids local installation for the user. Other modules are in preparation: continuous propulsion strategies, simple conic trajectory generation, data-volume modeling and estimation, generic modeling of an attitude control loop (in cooperation with Fabio de Oliveira Fialho from the University of São Paulo).

Started around 2013 with the propagator for the needs of BIRDY-T, DOCKS has involved several dozen student as interns or in short modules. At the time, engineers were trained on the – very expensive – STK software<sup>3</sup> (following the – toxic – commercial strategy of educational licenses that make them captive), the alternatives being STELA by CNES, in France, but limited to Earth orbit, or GMAT open-source by NASA’s Goddard Space Flight Center, but fixed-step (at the time), difficult to use, and limited in terms of perturbations. It had to be just as good, first in terms of validation, and even better to cover the advanced needs of BIRDY. A significant step in validation was achieved thanks to Tomás Nunes in 2024 (M2 of TUDelft, internship at CENSUS), who conducted comparative tests on a series of carefully chosen scenarios, between DOCKS, GMAT, TUDat<sup>4</sup> and FreeFlyer<sup>5</sup>. For example, in figure 5.3, after analyzing errors related either to the calculation method or the computing machine, a time step is chosen, and the integrators of the different software are compared. These tests show that the differences between DOCKS and other propagators, for a 24-hour trajectory, are within an ellipsoid of less than 3 cm in span, indicating that DOCKS is at the

<sup>1</sup>which now poses performance problems

<sup>2</sup>this module is, however, under maintenance due to observed regressions

<sup>3</sup>by ANSYS Government Initiatives (AGI)

<sup>4</sup>by Tudat Space, at Delft University of Technology, Netherlands

<sup>5</sup>by *a.i. solutions*

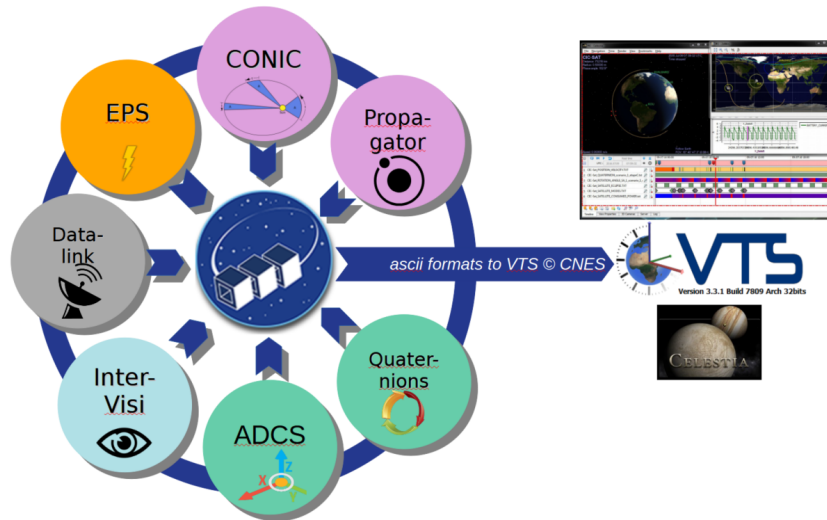


Figure 5.2: *Open-source software suite (GNU GPL v2 license), for early prototyping of a nano-satellite mission profile. On the right, all outputs from DOCKS are formatted for direct visualization by CNES' free software VTS (which uses the open-source CELESTIA graphics engine).*

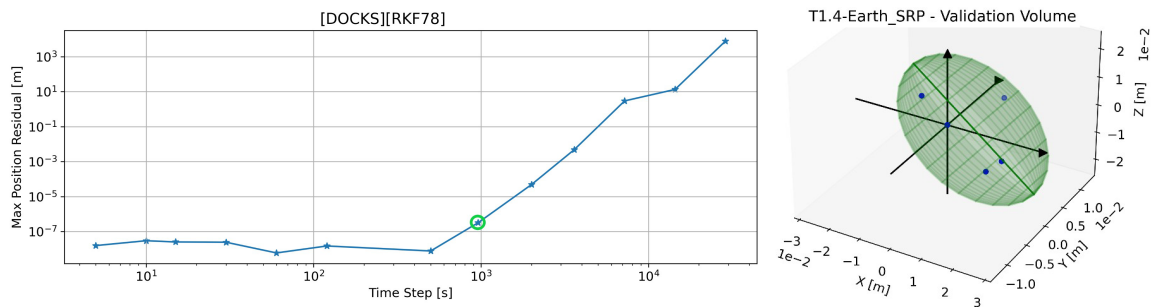


Figure 5.3: *Examples of DOCKS propagator testing. Left: choice of time step, in a regime of non-random numerical error (truncation error regime). Right: residuals compared with GMAT, FreeFlyer, and TUDat, after 24h of Earth orbit trajectory, considering radiation pressure, excluding eclipses. (T. Nunes, 2024).*

state-of-the-art.

This high level of validation is now the standard for all DOCKS modules. It has already been achieved with the propagator, pointing strategies, and intervisibility calculations. The idea then is to maintain and enrich the tests with each evolution, systematizing them by integrating them into a Continuous Integration / Continuous Deployment (CI/CD) production chain: the code manager (GitLab) includes the testing mechanism after each evolution and, at certain stages, also deployment tasks as a *release*. The CI/CD also ensures non-regression of the code and version coherence between modules.

My engineers have been directly involved in DOCKS to consolidate and professionalize developments at various stages, successively Sébastien Durand, Rashika Jain, Thibault Delrieu, and Feliu Lacreu, with a priority now on the CI/CD. The very concept of CI/CD can certainly extend to other tools like the MBSE approach or non-software tools, aligning with the goal of linking development phases from 0/A to E, as expressed for the future of the CENSUS ecosystem.



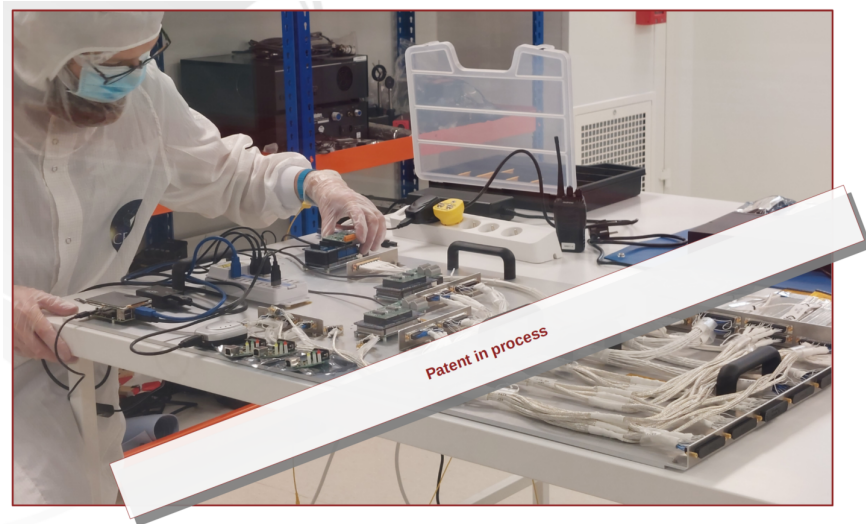


Figure 5.4: Cleanroom and simple functional chain “FLATSAT” test setup using COTS. A patent is being considered, requiring the above masking.

### 5.1.3 VEGA, integration

**VEGA** is the CENSUS cleanroom. A significant project of LabEx ESEP was to renovate a building in 2018 to create two cleanrooms, named ARIANE and VEGA by LESIA, which manages them: ARIANE houses LESIA’s thermal vacuum chamber, VEGA is dedicated to nanosatellites. The rooms are class ISO 7, ISO 5 under two available laminar flows, and meet planetary protection requirements. They can be completely isolated from any outside light and have two surveillance cameras. I oversaw the specifics for VEGA during the project, relying on the expertise of Jérôme Parisot, the cleanroom manager. Even though CENSUS’ activity in 2018 (year of PICSAT’s launch) was not yet integrating satellites in series, its inauguration by Alain Fuchs, then president of Université Paris Sciences & Lettres (PSL), was an important programmatic milestone. VEGA is regularly used by CENSUS for CASSTOR tests and student projects (from the OSAE Master’s and the graduate program), it has been rented by a company (GAMA, which launched its satellite in 2023 and conducted its first solar sail folding tests with us) and lent to integrate the MIRS instrument that will fly to Phobos on JAXA’s MMX space probe. Finally, VEGA stores a large part of our COTS and hosts our new “FLATSAT” test setup (see below).

Furthermore, closely linked to the cleanroom, the **VEGA Kit** refers to a collection of COTS purchased by CENSUS in 2019 and 2020 to get familiar with, before and instead of projects, what *NewSpace* can offer: reaction wheels, camera, onboard computer, solar panels, power board, telecom kit... Thus, we experiment with supply processes, especially after the global disruption caused by Covid-19, and we develop new educational modules, particularly in embedded electronics, for and by our students, such as for a Master Class, the OSAE Master’s project modules, or discovery internships in the graduate program. This “testing” activity is crucial for space systems integration and thus in the *NewSpace*. However, the skills are not taught in space engineering curricula and not at all in astrophysics researcher training. We get experienced with these “off-the-shelf” systems, sometimes disappointed when the *datasheet* does not match the product, which itself is not tested before delivery<sup>6</sup>, hence we can better advise projects in their development plan.

Another use of the VEGA Kit is to directly lend COTS to teams that want to get familiar

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<sup>6</sup>an unfortunate experience we had with a NANOAVIONICS reaction wheel, but also experienced by almost all CUBESAT teams based on conference feedback

or have a temporary need: we should intensify this approach in the coming years, with the creation of the Nanosatellites federation (CNRS research federation), the new Île-de-France Space Academy (see § 6.1.1 and the PSL “FabLabs” group).

We will continue in this direction by developing easily deployable COTS electronic setups for loans. These setups will be designed and carefully tested within the broader framework of the Nanosatellites federation: a hire is planned for 2024 for this purpose, and the approach is part of a broader *Hardware-in-the-Loop* strategy that would take over from the MBSE approach (§ 5.2).

#### 5.1.4 FLATSAT, validation

The **FLATSAT** is our latest means of testing and integration in a clean room, intended for phases C/D. Its purpose is also to raise awareness among a project team when they are preparing their development plan, thus in phase B, to properly size their phases C and D. My idea came from the need to demonstrate and test more or less complex functional chains of COTS (e.g., panels w. EPS card, or reaction wheel w. OBC w. imager...) without having to repeatedly build similar but never identical harnesses, which quickly become a forest of wires going in all directions. Our engineer and PhD student Janis Dalbins took charge of this project at the end of 2022. He enhanced it with a remote control concept based on his own experience with the Estonian nanosatellite ESTCUBE-2, to minimize the need for presence in the clean room. We are considering a patent, though it is uncertain if there is a market, hence the masking in Fig. 5.4 to avoid publication before filing (this is another injunction that hinders research, for PhD students who *must* publish their work!). In this spirit, contacts for “valorization” have been made, and a pair of students from the PSL-iTeams program have been involved with results expected in 2024. Manufacturing was subcontracted to SODITECH for all harnesses, and we sought the quality assurance expertise of Vincent Leray at HENSOLDT.

The relationship with HENSOLDT, or more precisely its expert V. Leray, is an example of opening up to industry since he is now involved in the CENSUS scientific committee.

FLATSAT is an important step towards the development of support in phases C/D. It is also part of the longer-term *Hardware-in-the-Loop* strategy.

#### 5.1.5 NANOSATGRID, operations

**NANOSATGRID** is a project proposed as early as 2022 for the operational phases (phase E) of nanosatellites. Its start has been chaotic: I gathered a consortium of 10 partners (6 academic, 3 private, 1 associative) around CENSUS and the company EUTELSAT GROUP to submit an application, which was not accepted, for funding from the Île-de-France region.

The ground station initially used for PICSAT was recovered by my engineer Sébastien Durand in 2018, with several interns involved. Modernized and then moved from its precarious location, we connected it to the open-source radio station network SatNOGS<sup>7</sup>, bringing together more than 3000 stations worldwide for reception only. SatNOGS was created by the *Libre Space Foundation* (Greece). Our approach allowed us to test our system and contribute to the community: we supported more than 9000 telecommunications passes in a year and a half. After another phase of work to build and install a maintenance frame, and replace the orientation motors of the YAGI antennas, it will be reconnected to SatNOGS while waiting to be used for transmission-reception operations.

The goal of NANOSATGRID is to go further and make the ground stations of consortium members interoperable in reception and transmission: the network thus formed represents a

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<sup>7</sup>SatNOGS Network, *Crowd-sourced satellite operations*, <https://network.satnogs.org/>

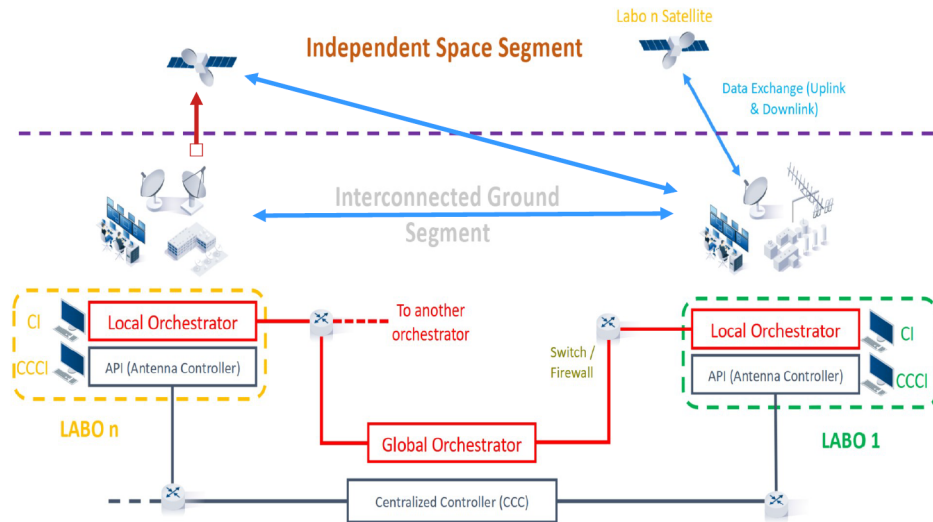


Figure 5.5: *NANOSATGRID* is a project to network academic and R&T ground stations of a consortium of French actors.

geographic and spectral coverage that can evolve over time and ensures a high level of redundancy during operations for members with their respective nanosatellites. Of course, the network also aims to open up to partners outside the consortium who want access to space telecommunications at a “R&T” price, since private sector rates are already out of reach for our academic community. Such a network requires adapting the partners’ hardware infrastructures and setting up, both computationally and materially, and adding an “orchestrator” and a “centralized controller” (Fig. 5.5). It is also planned to be able to disconnect from the network or connect an additional orchestrator like that of the SatNOGS network, which is the reason why the *Libre Space Foundation* had agreed to join the consortium.

While the issue of R&T, public-private structuring, image, societal, and even economic stakes are major, the project was inexplicably deemed “too” software-oriented by the Île-de-France region. What should we understand? The project remains current, and with our partner EUTELSAT GROUP, we are adapting it now to expand and address other funding opportunities.

### 5.1.6 AbC, flight experience

Finally, the internal project **AbC** (*Angle-based Correlation*) holds a special place: it does not target *support* for projects but a *technology*, potentially valuable. Initially responding to the need for autonomous navigation for an “augmented sensor” ([18, 25, 26]) in BIRDY-T, I hope to find much more general applications for it in *NewSpace*.

The goal of AbC is to provide a highly accurate absolute measurement of an optical *beacon* in the foreground of a star field. I proposed the method during my thesis, based on the observation that the angular distances of the *beacon* to nearby recognized stars in the image field were strongly correlated with each other. In the ideal case where the *beacon* would be at the barycenter of the recognized stars, the analytical formulation simplifies greatly and leads to equation 4.1 announced in the BIRDY-T presentation (§4.1). At this stage, simplifications are made such as the absence of optical aberrations, considering they can be calibrated later.

In 2021, when the ESA team in charge of the CUBESAT OPS-SAT was recruiting original algorithm ideas, I wanted to propose AbC. But the low stability of the satellite could jeopardize the AbC experiment itself. I then thought that AbC could actually help diagnose instabilities (serendipity!) and proposed it from this perspective. After some initial images

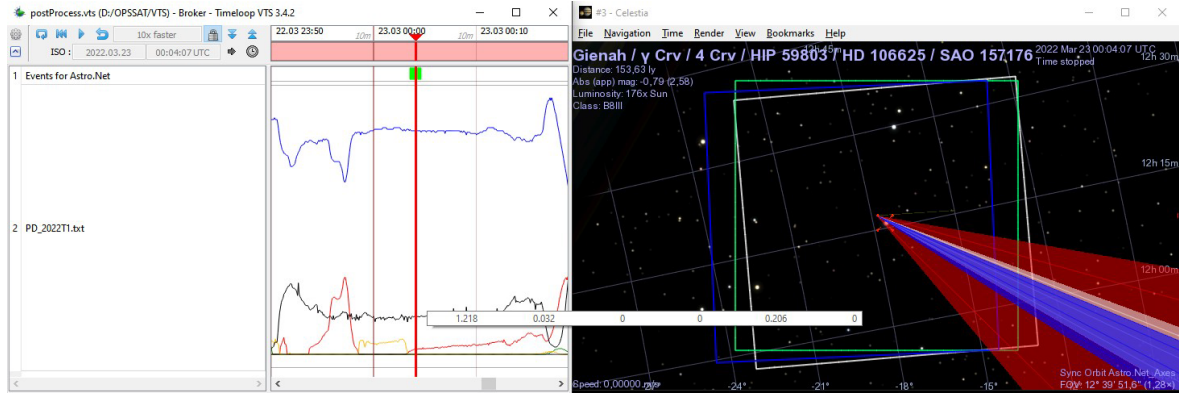


Figure 5.6: Expected  $10^\circ$  field of view (green), reconstructed from onboard attitude data (blue and left), actual from analyzed image (white).

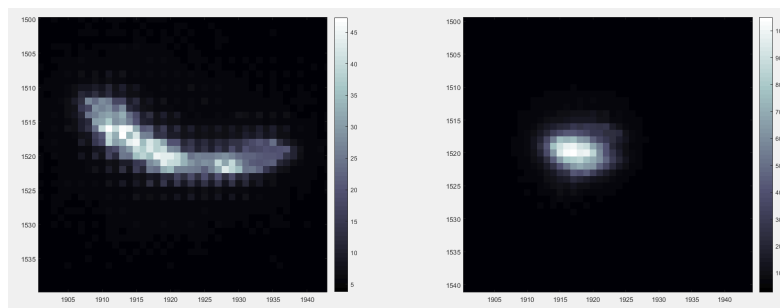


Figure 5.7: Five stacked images of Sirius without (left) and with recentring (right). Exposure of  $0.5s$ , i.e.  $2.5s$  in total.

taken in flight where I laboriously managed to detect stars, the project was funded by ESA with 50 k€. This allowed me to hire a developer passionate about astronomy, Pédro da Fonseca, already experienced in image processing. I developed a ground segment for mission preparation to calculate the pointings required from OPS-SAT and analyze the images returned to the ground. P. da Fonseca implemented my onboard algorithm in C++, aimed at cross-compiling for PC (for ground testing) and ARM (for OPS-SAT).

Incidentally, OPS-SAT also brings us experience with embedded code in a *NewSpace* platform, thus a phase E experience.

Even before the first onboard version, I obtained sky images based on my pointing requests and analyzed them: they showed that inertial pointings were biased (by a few degrees) and unstable as shown in Fig. 5.6. More importantly, they allowed me to quantify instabilities (Fig. 5.7) at low frequency ( $\leq 2$  Hz) as a *wobbling* effect of star images, and those at high frequency ( $\geq 2$  Hz) by the thickness of the trace, probably related to internal vibrations (magnetorquer jerks or reaction wheel vibrations). These simple images also quantified sensitivity based on stability, focal plane aging (distortions, hot pixels), as well as optical aberrations through simple analysis with **Astrometry.net** (Lang et al. [33]), an open-source solution for characterizing a sky image. These results were published, with the OPS-SAT team as co-authors (Segret et al. [34]). Thus, while “Nadir” pointings seem satisfactory for Earth observation, inertial pointings appear too demanding for the platform. Our results led the OPS-SAT team to try new strategies.

When our first version of AbC was ready in C++, we flew it and observed that the images were indeed taken, thumbnails around the expected stars well extracted... but there were no stars in the thumbnails, nor anywhere in the images! We continued the development and

to propose pointings, but we no longer managed to obtain stabilized images from OPS-SAT, despite the very significant involvement of the entire OPS-SAT team in this regard. The satellite's pointing seems to degrade inexorably and atmospheric drag is increasingly felt as it descends towards the atmosphere (reentry estimated for 24/05/2024 according to ESOC). It should also be noted that we had a secondary interest in working on OPS-SAT, given that the attitude control system selected in COTS was the same as on PICSAT, that of BERLIN SPACE TECHNOLOGIES... seemingly with the same poor result.

OPS-SAT remains, nonetheless, a very rich experience. Exciting for me as well, as I found myself reliving the rhythm and challenges of space operations that I experienced during my time with VENUS EXPRESS.

- For AbC, we have gained the conviction that onboard processing is feasible to characterize platform stability through intensive measurements (without downloading full-frame images to the ground), although its sensitivity to all sources of errors (cosmic, aberrations, stray light...) remains to be tested. In this regard, partial PhD funding was obtained in 2024.
- Onboard intensive processing (images not downloaded to the ground) also allows us to estimate what alignment corrections need to be applied to each contributor in the entire error chain (solar sensor, star tracker, imager), which as far as I know is quite novel.
- We have built a database of images on which we can test this algorithm's sensitivity on the ground, at least partially, in view of a future flight opportunity.
- AbC is therefore a serious solution for in-flight commissioning of nanosatellites, a phase still poorly covered these days, opening a possible avenue for valorization to the "real-world economy" (as they say), and more importantly for CENSUS, improving practices in *NewSpace*.

Furthermore, we already knew that *NewSpace* cameras were often ill-suited for sky observation (low sensitivity, RGB matrix, strong aberrations), and that onboard image processing is an area where we need to invest, again from a "Hardware-in-the-Loop" perspective. OPS-SAT reveals another potential issue: while *NewSpace* tests for attitude control may be relevant in the context of Earth observation, we, as astrophysicists, hope to use them for sky observation as well, perhaps wrongly.

## 5.2 Engineering Methods

Beyond the means implemented within CENSUS for the various phases of nanosatellite development, such as the PROMESS Plateau or FLATSAT presented earlier (§5.1), I have emphasized so far on the development of engineering methods, targeting phases 0/A. These methods aim to establish a "mission profile" and to structure the dialogue for the entire project in its subsequent phases.

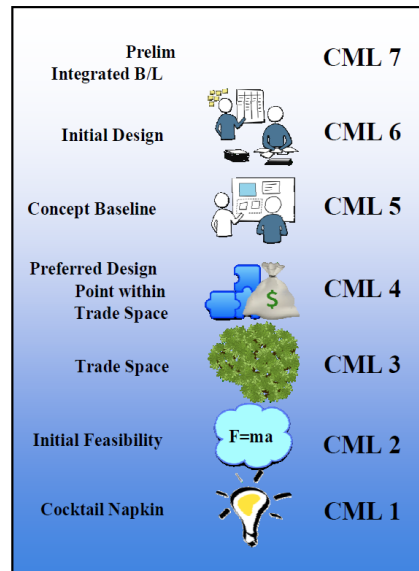
### 5.2.1 Finding our Place: CML 1 to 5

Concurrent engineering is perfectly suited to structuring a scientific nanosatellite project. Agencies such as CNES, ESA, and JPL for NASA, and probably others, have long explored these practices for their space missions. Tools have been developed, supported by "services": for example, CNES conducts a "PASO study", led by a highly experienced engineer, which produces a report on the technical, calendar, and budget feasibility of the project. This



## Concept Maturity Level: CML

- ▶ Created by Mark Adler, JPL
- ▶ Inspired by TRL scale
- ▶ Covers the phase of mission concept formulation from “cocktail napkin” to NASA PDR
- ▶ **PDR = CML 8**
- ▶ Embraced by NASA PSD and now an integral part of JPL’s formulation approach



▶ 8

NASA Jet Propulsion Laboratory

July 6, 2009

Figure 5.8: *Summary of the Concept Maturity Level (CML) scale, excerpt from Vane [35].*

report serves as a decision support for project funding and planning. During such a study, a concurrent engineering campaign can be organized, employing tools like STELA (orbit production and analysis in the Earth environment), IDM-CIC (3D platform illustration, collection of characteristics needed for system budgets, visualizations), or VTS (visualization of spatial data in a mission scenario). Other CNES tools exist, open to the community or internal, for instance for thermo-mechanical sizing or radiation environment. ESA has its equivalent with the Concurrent Design Facility (CDF) at ESTEC, utilizing different tools. JPL has explicitly developed the notion of service, such as the possible assembly of a “Team-X”, composed of project team members and JPL experts. JPL’s approach is to deliver “products” tailored to the project’s maturity. For example, a product could be the project narrative for funding application or a costing operation, implying cost optimization through prospective technology use or development.

In such an environment where the professionalism level of concurrent engineering is so high, are we at risk of redundantly doing what is already done, but worse? The answer lies in “metrics”. At the start of a project, it lacks its metrics, i.e., key parameters that will express the level of response achieved by a particular solution. During the PASO study for the NOIRE project, I quickly noticed that CNES experts supported its strong potential but expected figures from us, the scientists, that we did not have the human resources to provide. CNES’ involvement thus allowed us to decompose the scientific expectations as far as possible and concluded that there were no identified blocking points at this stage. In other words, to go further, a structured scientific specification was needed, and under these conditions, funding agencies would listen very favorably, as evidenced by the funding already obtained, such as Erwan Rouillé’s co-supervised PhD.

While our scientists’ instrument proposals follow a well-structured path of scientific specification, nanosatellite projects did not have this approach. Not surprisingly, as the *NewSpace* paradigm invites us to simplify to accelerate. But the result is that the space agency *does not understand* what we want: it positions itself as an expert in platform issues but cannot

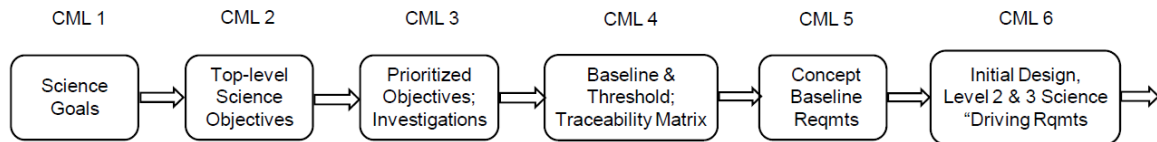


Figure 5.9: *Objectives associated with each level of Concept Maturity Level (CML), excerpt from Vane [35].*

replace us in designing the observation strategy.

In fact, JPL theorized this difficulty as early as 2009 with a maturity scale, the Concept Maturity Level (CML, Vane [35], Wessen et al. [36]), where the preliminary definition review is organized when the project reaches CML 7 (see Fig. 5.8 and 5.9). In a typically American format, the “Team-X” aims to gently challenge the project team so that a strong positioning emerges: one that allows for securing funding, securing the schedule, and achieving the initially set objectives (and therefore formulating the right objectives). In short, this is the project manager’s mission! I encountered another formulation during my experience at EADS Launchers (now ARIANEGROUP) in the form of "OCOTOQ" for On Cost, On Time, On Quality.

CENSUS positions itself at the core of Science with the Paris Observatory-PSL. It seems natural to position CENSUS in the *NewSpace* landscape as a service for maturing projects until space agencies (for example) can take over, starting from CML 4 or 5. From there, platform-level analyses are conducted with good visibility on their scientific consequences and, even better, a good capacity for adapting the observation strategy (thanks in particular to the detailed MBSE approach below). This is exactly the dialogue that CNES wanted in the PASO study for NOIRE, and the one we successfully had during the PASO study for CASSTOR. This positioning has thus motivated my way of adapting or creating engineering techniques, in a context of primary use of “PROMESS campaign” as will be presented now.

### 5.2.2 PROMESS Campaigns

Let’s indulge a bit in marketing by referring to the “PROMESS Plateau” to designate the concurrent engineering center of CENSUS. Despite the current trend to reduce all know-how to a matter of tools, it is not enough (unfortunately) to gather a few people in the same room with expensive licensed software to bring forth a space mission concept. Even by assembling brilliant students, it will not suffice: the students may be sensitized but no useful mission concept will emerge. Because a concurrent engineering campaign must be prepared and aim for specific objectives.

#### Preparations

A typical PROMESS campaign format is a full week of immersion at the PROMESS Plateau. A variant is 5 non-consecutive days. Sometimes, contributors are also connected remotely, hence the importance of excellent sound to support a full day of connection. A work program is carefully prepared in advance:

- Identification, with the scientific manager and project manager, of campaign participants and their roles (optics, thermo-mechanical, system engineering...). Indeed, it is not uncommon for certain skills to be lacking at the beginning of a project, so objectives must be adapted.
- Selection of a concrete problem to be solved during the campaign. To do this, I drew

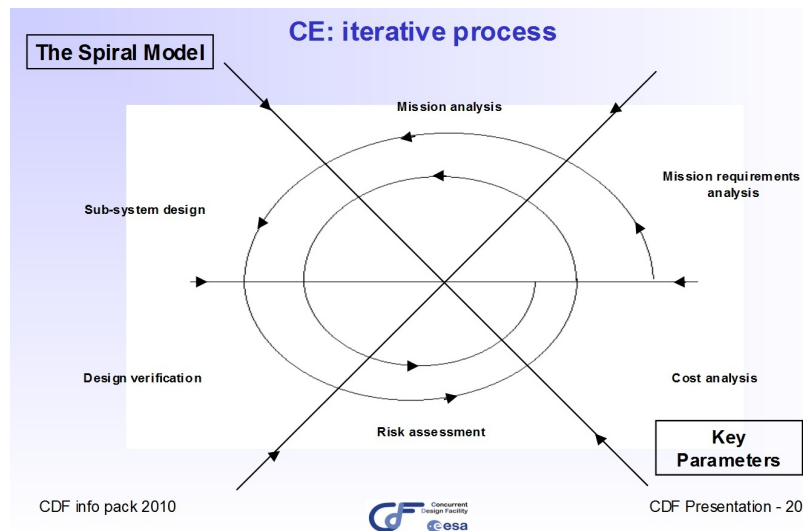


Figure 5.10: *Tool for elicitation, Concurrent Design Facility (CdF) of ESTEC/ESA.*

inspiration from JPL/NASA techniques and propose formulating the objective based on the CML:

- Formulation of the project’s “manifesto” (mission statement pitch), for example to respond to a call for proposals.
  - Specification of the “metrics” for the future mission.
  - Structuring requirements, particularly the lineage of scientific specifications towards engineering requirements, this lineage being the means of arbitrating at the appropriate time.
  - MBSE (see below), in this case a significant initial modeling effort returns to CENSUS, with the scientist’s help for their part, with the aim of transferring MBSE to the project team during the campaign.
  - It could also involve risk analysis or costing (for us, a comparison to the state-of-the-art) but to date we have no experience in a concurrent engineering format.
- Planning, invitations, and team sensitization for the campaign.
  - Ordering coffee for 5 days (yes!) and animating the campaign.
  - Preparation of a deliverable (produced by the team, with CENSUS consolidation).

### Animation

Among the irreplaceable skills, we must highlight those of researchers and engineers in instrumentation. Their presence on a PROMESS Platform ensures success. Ideally, we should also add the expertise of platform engineers and operations.

However, to focus discussions towards a common objective, we also need the know-how of the facilitator, who also requires tools, primarily methodological ones:

- One I systematically use is the **spiral model**, borrowed from the *Concurrent Design Facility* of ESTEC/ESA (Fig. 5.10). I primarily use it as a tool for brainstorming with the project team. It allows for an intermediate recap of campaign progress, typically two to three times in the week.



- This spiral model encourages, among other things, the identification of Key Parameters, also referred to here as “metrics”. Although I don’t have a specific tool for identifying them, these metrics subsequently become instruments for project definition and arbitration.
- The **Manifesto** is another exercise in brainstorming, serving as a deliverable for the campaign. It synthesizes the project, recapping the fundamental reasons for undertaking it and the expected achievements. Inspired by JPL, it’s a powerful tool in response to calls for proposals.
- **Spreadsheets & Lists**. Naturally, compiling requirements, specifications, or constraints, as well as identified risks, requires a tool. Instead of using dedicated and paid management tools (like DOORS<sup>8</sup>), we use simple spreadsheets, albeit with a “lineage” parameter among requirements. A model has been established following mission steps (from pre-launch to end-of-service). This approach is sufficient for a limited number of specifications (up to a hundred, typical in the early stages of a nanosatellite), especially since their formulation is initially exploratory and requires numerous revisions.
- **MBSE** is the standout feature of CENSUS: with my systems engineering background, I aimed for an approach integrating functional analysis. Process maps enforce a termination vision in nanosatellite mission design. These maps are developed just afterward. MBSE aims to include identified “metrics” and quantitatively reflect the scientific coverage achieved, updating it during arbitrations and development. While teams quickly embrace MBSE, its full adoption is less straightforward. Training in this approach is also challenging and remains a future objective of mine.

### 5.2.3 Functional Analysis: SADT and MBSE

There are numerous methods of functional analysis taught in systems engineering courses, which students often struggle with if they lack technical maturity. Among these, I discovered at DASSAULT AVIATION the process maps, using the syntax of “SADT” diagrams. They help describe any complex technical system, for example, a nanosatellite, a part thereof, an organization (such as the project team), or the nanosatellite mission itself. While SysML and UML are often highlighted and proposed in software tools to be broken down into documentary stacks (at a low level), I believe this is a poor choice: UML targets software, not systems in general (human, material systems...) and imposes too early a typing, as it is too low-level. Its insufficiency is acknowledged (Normantas et al. [37]); it is even proposed by Marca [38] to complement UML with SADT. Conversely, when it comes to software, indeed, it is proposed to complement SADT with UML (Baldwin et al. [39]).

I have adopted SADT in all functional analyses I have supported: the ground demonstrator for BIRDY-T, the instrumental simulator for NOIRE, various nanosatellite mission profiles, notably for CURE (and its derivative mCure), CASSTOR, and soon TERACUBE.

#### Simple yet effective modeling

Without detailing here all SADT concepts, heavily influenced by IDEF0 modeling, it is useful to mention a few principles (See Fig. 5.11). Readers interested in the genesis of these models from 1970 to 1981 can refer to Ross et al. [40].

It is a notebook of hierarchically organized process maps, each map presenting a “system” described by its main processes (boxes, action verbs), receiving or using an input flow on its left and producing an output flow on its right. Some input flows can be considered “triggers”

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<sup>8</sup>by IBM Engineering Requirements Management

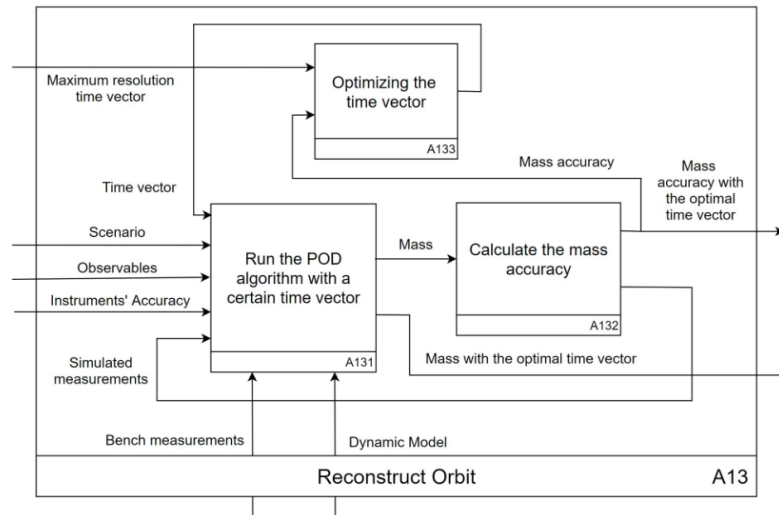
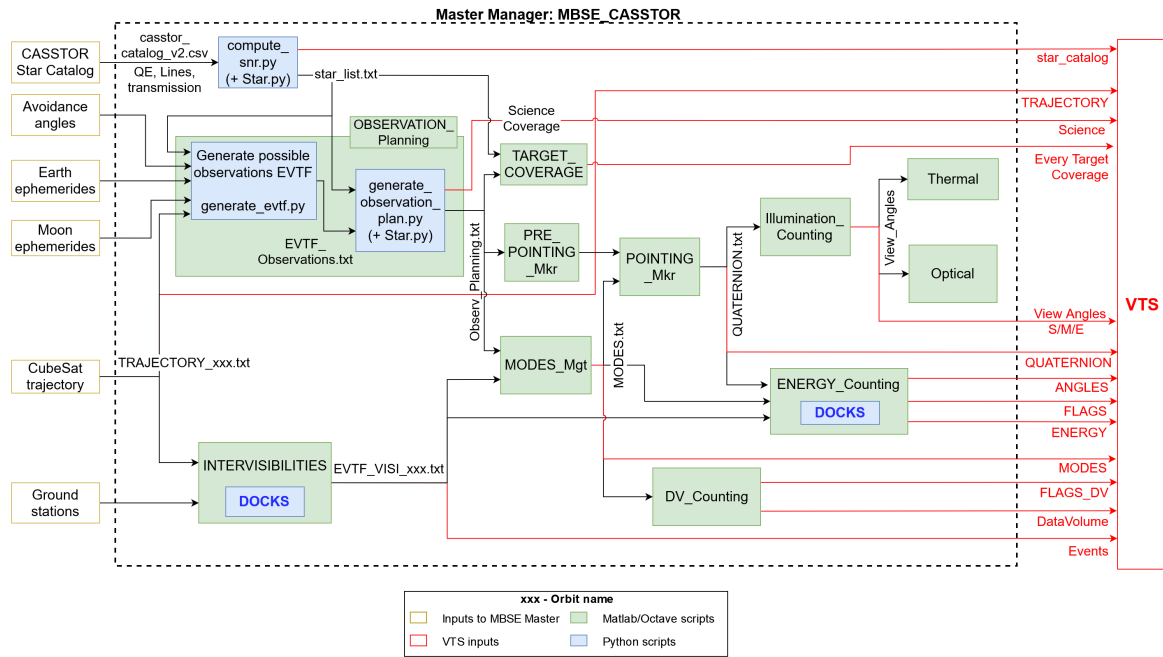


Figure 5.11: Example of SADT for Module A13 of the ground demonstrator for BIRDY-T (Abd El Dayem, 2020, internal ref. BIRDY GEO-005).

and are represented as arriving from above, or as “mechanisms” (or resources), arriving from below. The recommended number of processes is 3 to 6; otherwise, decomposition is necessary. For me, the goal of SADT is to identify transformations (processes), to identify what enables them (inputs), and what they serve (outputs). The aim is not to be exhaustive but coherent: interfaces should be consistent from the box of one map to the sub-map describing that box. The objective is to identify “who” does “what”, but not “how”, independent of their future implementation (for code or for a system) or the organizational chart (for an organization). It is far from a SysML model but also from an algorithm or a MATLAB/Simulink-style automaton, which are software-oriented.

In fact, several initiatives aim to develop software for tracing and monitoring a design, often with the intention of automatically generating code or code skeletons (if only for documentation). This is the case at the Concurrent Design Facility of ESTEC/ESA with its OCDT, Open Concurrent Design Tool, which relies on the ECSS-E-TM-10-25 normative reference. But the challenges are different from those at CENSUS: besides the well-understood commercial interest for companies developing “tools” (I encountered the expression “sales & consulting cash cow” regarding UML), ESA must accommodate dozens of professionals, especially industrial ones, whose contributions have strong contractual dimensions. ESA undertakes a mission to structure methods and dialogues within the community. Teams supported by CENSUS are small and aim for responsiveness and flexibility in achieving scientific coverage: overly complex tools would likely hinder team maturation and commitment and divert attention from observation strategy. However, it is not excluded to migrate to OCDT-type tools. Our adoption of CNES’ VTS software also leads us to adopt CCSDS data formats. However, it will be necessary to ensure that these tools are as transparent as possible for project teams.

Our consulting role at CENSUS is to establish a scientific coverage model of a project. Thus, it is not about producing a “design”, which is the role of the project team, with its own methods and tools. Nor is it about engaging in an instrumental simulator that could take years without meeting the objective of dialogue within the project and with partners. Therefore, our **MBSE approach** is to model the “conditions” under which observation is expected: the associated analysis then tracks *when* these conditions are met and, consequently, what quantitative level of observation is achieved (SNR, spatial or temporal coverage, observed

Figure 5.12: *MBSE Architecture for CASSTOR in 2023.*

targets...). The *system* we design in a “mission profile” is the set

$$\{\text{Nanosatellite} + \text{Trajectory} + \text{Ground segment}\},$$

combined with a given calendar projection.

The functional analysis of this system leads to a model very close to an SADT diagram, with outputs calculated based on the project’s “metrics” (Key Parameters of the spiral model), then formatted for visualization in VTS. The modeling is specific to each project. Take the example of CASSTOR, which underwent a PROMESS campaign in preparation for the CNES’ PASO study, and whose MBSE architecture is shown in Fig. 5.12:

- The different boxes are “models”, small codes in various languages (mostly GNU Octave or Python, sometimes bash, and a shared directory). Some models use DOCKS modules. Outputs include chronograms, event files, and orientation files in quaternions or vectors, viewable in VTS.
- The initial architecture was developed by myself, adapting bricks from previous MBSE architectures, as the needs were generally recurring. It is prepared in advance of a PROMESS campaign. The same applies to scientific models agreed upon with P.I. and P.M., here for the star catalog, planning strategy, and conditions for successful observation (including angles to avoid light pollution). After an initial campaign in 2021, the architecture was enhanced and updated.
- Each box is under the responsibility of an individual (from the project team or CENSUS) who clearly sees whom they depend on and to whom they provide data. Updating all models can be complex, but functionally, each can work between updates with a coherent dataset. Therefore, naming and versioning of data are important elements of the MBSE approach.

The issue of synchronization among multiple actors should be at least partially addressed by employing CI/CD during the course of a campaign. Even for large data, solutions compatible with GitLab exist (*git-lfs*).

A budget request for a *platform engineer* is currently under review for 2024 by the Académie Spatiale d’Île-de-France (See 6.1.1). The mission of this engineer will cover the entire process of campaign preparation, execution, and knowledge capitalization, for both engineering and academic or Vocational training. This illustrates a strong development focus for CENSUS.

### Tool or Method Issue?

We use MBSE as *model-based system engineering* from a semantic standpoint: observation strategy, optical design, fine pointing performance... all these aspects are consolidated through modeling the observation conditions where project metrics are deeply embedded in the models, which only *verify* if these conditions are met during a mission simulation.

When presenting this approach under the name MBSE at a specialized systems engineering conference (SECESA, organized by ESA and CNES), I was told it was more about mission models, implying it was not MBSE. I stand by this term and would rather urge SysML advocates to abandon it in their marketing of constraints they impose on clients. Indeed, while acknowledging the need for specialized tools beyond a certain level of complexity, modeling tools applied to CUBESATS seem to follow an ideology of “all tool” that distorts the purpose of concurrent engineering. For example, a requirements manager will not lead to modifying light avoidance angles, whereas my approach will. Yet such a manager would have demanded substantial effort on non-priority aspects in the early stages.

The potential of our MBSE approach at CENSUS should be noted:

1. It structures the project and the team itself, evolving easily over time. While there is always uncertainty when finalizing instrument or platform design assumptions, here, a termination vision is imposed from the start. It allows each specialist to explore options in their own autonomy space, as the entire MBSE model is distributed to everyone and remains functional. Each knows their expectations and the final goal to achieve (schedules maximizing science coverage).
2. It could become contractual in tender calls, for critical systems or the entire platform which, with nanosatellites, increasingly falls under the responsibility of the scientific team (instead of agency responsibility in conventional space). With its compact format and focus on open-source tools (at least so far), a complete MBSE modeling is portable and easily transferable to other computers (though Macs are more capricious with VTS, a Linux virtual machine or Docker are feasible). For instance, the data set for CASSTOR output from the PROMESS campaign was 685 MB uncompressed (excluding bibliography). Although we do not yet have experience including our MBSE in contractual clauses, it appears easier to enforce deliverables compatible with our MBSE (CIC-CCSDS format) than to be imposed with paid tools and proprietary data: MS Office for VBA and other macros, Sharepoint or simply Google docs, STK, Matlab, Thermica, CATIA or GoogleSketch... to name a few, often popularized through the toxic strategy of free license addiction for education. On the same principle, and here too we lack experience, MBSE modeling should also be able to support D/E phases, for ground and in-flight testing of subsystems, integration, and overall validation, with a precise view of the scientific impacts of any modifications.
3. It could also be applied in conventional space at the instrument level, when a proposal is submitted for a multi-instrumental mission. In this case, the mission profile is not easily negotiable but its consequences on scientific coverage are directly analyzable, justifying early dialogue with agencies based on models (trajectories, data attitude flexibility, geometric event calculation). Even if teams are accustomed to maturing in

a more structured and documented manner than with nanosatellites, they would gain adaptability and arbitration capacity. This could motivate an approach to training researchers and engineers.

4. It is likely the same for non-astrophysical scientific space missions or even high-complexity non-space projects. Hence, potential value for continuing education.

In 2018, CNRS suggested CENSUS conduct an ANF (National Training Action) on this MBSE approach, alternating annually with one recently set up by OVSQ called “concurrent engineering for preliminary projects”. For such training that touches significantly on interpersonal skills for a non-space audience, the minimum format I targeted was 5 days, equivalent to a PROMESS campaign (which our subsequent actions will confirm). However, there were too many constraints: CNRS agents could only arrive on Monday noon at the earliest (travel outside weekends) and leave by Friday noon; they had to be housed and fed nearby or transported; no budget was allocated to CENSUS, neither for setting up nor for running the training. CENSUS could not undertake such self-financing effort and did not pursue this attempt.

Nonetheless, there remains potential for continuing education, which will be explored within the framework of the Académie Spatiale d’Île-de-France (See §6.1.1).

### 5.2.4 Intermediate assessment

We do not yet have sufficient hindsight to say whether PROMESS campaigns, SADT functional analysis, and MBSE architecture will durably and positively impact B, C, D, E phases of projects. Particularly, a long-term challenge seems crucial: if these phases maintain the MBSE architecture developed in phase 0 as their guiding thread, namely its maintenance and use as a reference in reviews and specifications with partners, then our engineering methods will have demonstrated their structuring power. We felt reassured to see their good acceptance by the projects themselves, by CNES for CASSTOR, and by several external partners. The ultimate step would be to authorize supplier payments based on tests directly derived from MBSE simulations: this will be enabled by the already mentioned Hardware-in-the-Loop culture.

We still need to promote our methods in other sectors and complement them with automations and coherence checks, inspired by the CI/CD that I intend to adopt for CENSUS. Of course, we must also explore possible interfaces with agencies and industries, while remaining vigilant about captive licenses: ESA’s *OCDT* tool, CNES’ *IDM-CIC*, *STELA* (and more), JPL’s *Team-X* and  $\alpha$ -*Team* methods...

Finally, recurring issues in astrophysics (notably) remain poorly covered in CENSUS. They will require dedicated developments on a nanosatellite scale. Specifically, the needs to predimension the following aspects:

- In DOCKS: onboard power budget (an *EPS* module was initiated in DOCKS but needs further review and extension), link budget (data volume, simplified models are available), continuous propulsion strategies to insert them into trajectory propagation;
- Attitude control requirements, a collaboration on this theme was initiated in 2022 for CASSTOR based on experience with available PICSAT data, by Prof. Fabio de Oliveira Fialho from the University of São Paulo (Brazil), [41];
- Thermo-mechanical design, expertise should prevail over tools, requiring an approach limited to modeling a few *nodes* to analyze thermal inertias and passive or active control options (considering adopting a python code from Tristan Buey of LESIA);

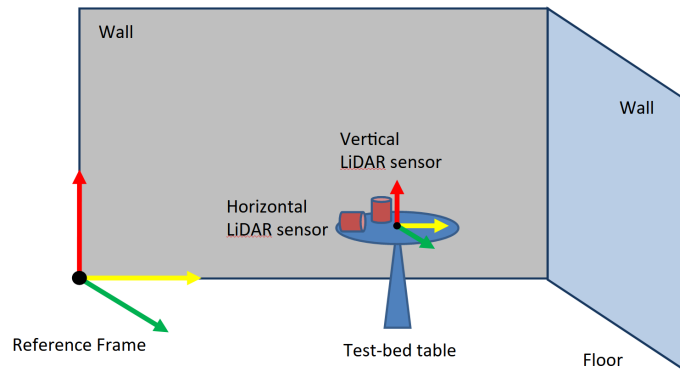


Figure 5.13: *ADCS testing platform proposal (Hoang, 2017).*

- Electromagnetic compatibilities in conduction and radiation, an initiative is being studied for NOIRE with ARIANEGROUP and ISAE-SUPMECA, early analysis aiming to provide solutions to industrial partners.

## 5.3 Nothing without individuals

### 5.3.1 PhD students

Prof. Benoît Mosser, as the educational director from the beginning of CENSUS, has durably established us in PSL’s programming with a substantial and recurring budget. I supported this effort by proposing a candidate for the PSL-ITI (*Institute of Technology and Innovation*) pre-doctoral program in 2014, Gary Quinsac. He then became our first “CENSUS PhD student” in 2015, the first thesis I co-supervised: the thesis was on the attitude control of nanosatellites equipped with continuous propulsion ([17]). As we already noted with figure 4.2 for BIRDY-T, this thesis resulted in a warning to the community and the associated article [42] is among the most read of those I have coordinated, with over 1500 views and 19 citations reported by RESEARCHGATE<sup>9</sup> since 2020.

In parallel with this thesis, in 2016, B. Mosser set up a co-supervised thesis with USTH (*University of Science and Technology of Hanoi, Vietnam*) for the PhD student Hoang The Huynh, whom I then co-supervised. With H. Hoang, we aimed to create a 3-degree-of-freedom testing platform, controlled in rotations by 2 lidars, to stimulate the attitude control systems of nanosatellites (Fig. 5.13). Unfortunately, after the first year, Vietnamese funding was insufficient, and H. Hoang had to prioritize an engineering job in the industry. The design of the envisioned tooling signaled a complex project. Today, with the collaboration of the University of São Paulo (§ 5.2.4), we are resuming this path by combining simulations and impulsive tests, with a view to a specific section in DOCKS.

After the CURE project, the ties between CENSUS and the University of Tartu (Estonia) have strengthened. We hosted the PhD student Janis Dalbins as a visitor, who effectively contributed to the work on embedded electronics, an area where I lacked expertise. I was proposed to become his co-supervisor, alongside Andris Slavinskis and under the direction of Mart Noorma. J. Dalbins was in charge of the telecommunications for the Estonian nanosatellite ESTCUBE-2 (Fig. 5.14, launched at the end of 2023, which experienced a separation failure and re-entered the atmosphere with the launcher) and supervised many students from Tartu in electronics. ESTCUBE-2 was a challenging project, both technically and programmatically, spanning over 7 years, building upon and complicating the legacy of ESTCUBE-1.

<sup>9</sup><https://www.researchgate.net>, visited on 03/18/2024



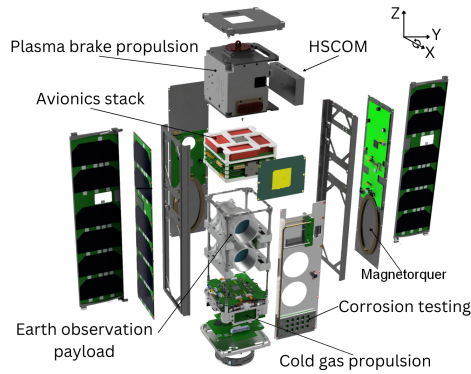


Figure 5.14: *Exploded view of ESTCube-2 (Dalbins et al. [2]).*

The goal was to lay the foundation for an “MAT” (*Multiple Asteroid Tour*) nanosatellite with continuous acceleration by an electric sail, “eSail”. My role was to consolidate the end of the thesis by structuring all the technical and managerial experience acquired by J. Dalbins in this project, which had a chaotic but highly valuable journey [2]. Although the satellite was delivered on time, it was made complex by fragmented funding, which led to the multiplication of secondary payloads (brought by the funders) and imposed numerous mission trade-offs, including the postponement of the *deep space* demonstration. This co-supervision of the thesis brought the culture of electronic testing to CENSUS and allowed us to propose several educational modules for the observatory’s curricula.

In the NOIRE project, CNES support enabled the initiation of a thesis to structure the scientific requirements of a project capable of serving numerous themes. Erwan Rouillé completed an end-of-study internship and then a first year as an engineer around the idea of a “Radio Source Tracker” (RST), under my co-supervision, with Baptiste Cecconi from LESIA. The RST had been identified as a need, functioning by recognizing known radio sources in the sky to determine the overall attitude of the swarm (each nanosatellite having its own attitude control), and also as a demonstrator of the swarm interferometry concept. It allowed us, in an exploratory way, to set a work plan for E. Rouillé’s thesis that followed (still ongoing), under the direction of B. Cecconi and with my co-supervision. The technical and technological scope appeared immense, and we chose the following priorities: developing two key scientific cases (in terms of funding), in solar physics and planetary science, setting their technical requirements, and initiating an instrumental simulator that will illustrate these two cases. Our goal will be to model the instrumental response in the presence of different sky models proposed by the literature, knowing that the latter is simply not known at the targeted frequencies ( $<10$  MHz). Meanwhile, we are postponing to more financially abundant times other highly prioritized questions that we cannot yet address, such as electromagnetic compatibility (a study is nevertheless initiated, Cf. §5.2.4), clock synchronization, or design of deployable antennas.

These theses illustrate the importance, for me, of the *Deep Space* exploration theme. As I noted when presenting *NewSpace* (Chap. 3), Italy has not been mistaken about it.

The Polytechnic University of Milan (*Politecnico di Milano*) has become a major player, with several articles closely related to my favorite subject, interplanetary navigation. I therefore wanted to get closer to it. After discussions at conferences, Prof. Francesco Topputo invited me to Milan to visit his facilities and offered me, at the beginning of 2024, to be the reviewer for his PhD student Eleonora Andreis, who successfully defended her thesis on May 9, 2024. Her topic, “Autonomous Vision-Based Navigation for Deep-Space CubeSats: Algorithm Development and Hardware Validation”, completely overlaps with CENSUS priorities and further justifies them. This thesis, and the work of F. Topputo’s team, represent an am-

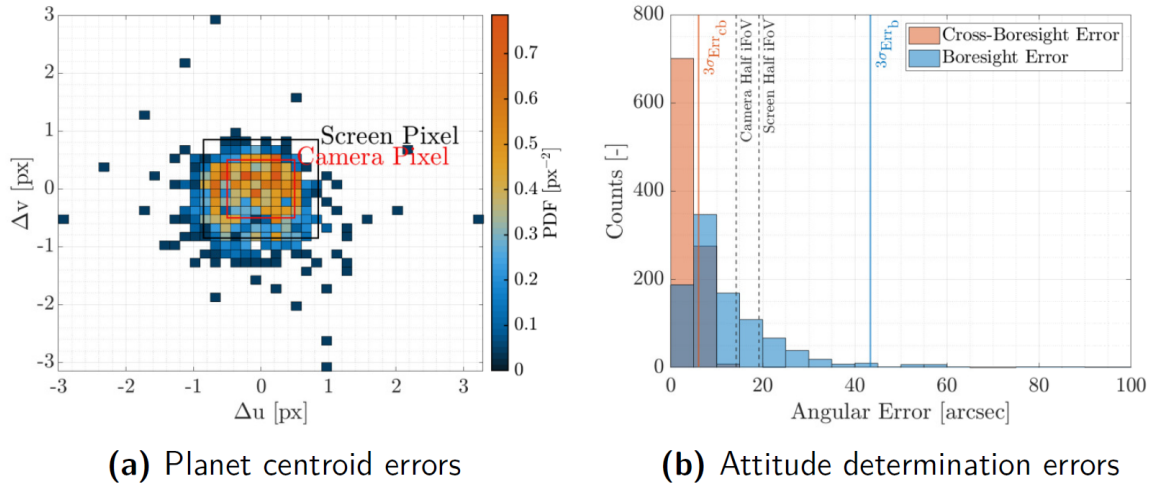


Figure 5.15: *Statistics of the behavior of a centroiding algorithm in a Hardware-in-the-Loop simulation, including a simulation injected into an optical setup and the processing of the obtained image (Andreis [43]).*

bitious initiative in *Hardware-in-the-Loop* approach: for example, Figure 5.15, extracted from E. Andreis’ manuscript [43], shows the performance of a centroid calculation algorithm after injecting a simulation into an optical bench (RETINA) and processing the image produced by a sensor. Perhaps we could learn and contribute: thus, we might submit algorithms to their facilities (UKF, AbC) and benefit their *deep space* projects, share our experience with COTS (camera, FLATSAT), and for the evaluation of attitude control systems. Having a *deep space* contribution on an Italian nanosatellite could perhaps be a beginning towards a French *deep space* nanosatellite.

Finally, I have served as a member of the thesis monitoring committee for the PhD student Ryan Dahoumane, alongside Josselin Desmars from IMCCE, since 2023. His subject focuses on the study of the long-term dynamics of the distant satellites of Jupiter and Saturn, under the co-supervision of Kévin Baillié and Valéry Lainey, also from IMCCE.

### 5.3.2 The engineers of CENSUS

Pierre Drossart and Coralie Neiner obtained and renewed various funding, especially from PSL. Thus, we have sustained a second full-time position in CENSUS, albeit through fixed-term contracts. I have successively supervised three engineers:

- Sébastien Durand (DOCKS and Ground Station),
- Rashika Jain (DOCKS, MBSE, and OSAE),
- Feliu Lacreu (DOCKS, MBSE, ground station, PSL-Week, and OSAE).

I also hired, under other budgets, the engineer Grégoire Henry (initially an intern and then an engineer) for the functional analyses of the ground demonstrator of BIRDY-T, and the assistant engineer Kirill Anohin for its integration. Occasionally, I brought in engineers Thibault Delrieu (CPU diagnostics and DOCKS parallelization) and Louis Le Leuch (ground station) for reinforcements. Finally, for the AbC project, I specifically hired the developer Pedro da Fonseca (see §5.1.6).

The PhD student Janis Dalbins was also hired under an engineering contract in parallel with the end of his thesis. Thus, since the creation of CENSUS, I have supervised 8 engineers and 1 assistant engineer.



### 5.3.3 Educational contributions and internships

From its creation, CENSUS planned to play a role in the curricula of the Observatoire de Paris-PSL, mainly thanks to the interaction maintained by B. Mosser, educational director of CENSUS.

Rather than offering lectures on nanosatellite systems engineering, I proposed topics for student “project modules”, which I then supervised or co-supervised with my team, in various formats:

- **Professional Master “Tools and Systems of Astronomy and Space” (OSAE, Observatoire de Paris-PSL with 3 co-supervisors):** since 2014, one to three projects per year have been proposed, representing 10 days of a student pair received at CENSUS, per topic. The topics targeted contributions or analyses on or with DOCKS, or electronic assemblies with COTS from the VEGA KIT.
- **AstroParis Graduate Program, Observatoire de Paris-PSL:** since 2021, we have set up a MasterClass mockup on the theme of “functional chain tests”, coupled with the project modules of the Master OASE, using the VEGA KIT and soon the FLATSAT.
- **PSL-ITI, then PSL-iTeams:** ITI was a one-year pre-doctoral program established by PSL focused on entrepreneurship, where I mentored two teams, one in 2014 that included our future PhD student G. Quinsac around continuous propulsion, and another in 2015 around asteroid mining. In 2023, PSL’s iTeams program, also focused on entrepreneurship and research valorization, succeeded PSL-ITI. I proposed two topics there, one on AbC which I mentored and another on FLATSAT mentored by Janis Dalbins.
- **Astronomy and Biology Summer School, Tartu, Estonia:** I participated in two editions of this school (2018 and 2019), organized by Prof. Dr. Wolf Dietrich Geppert from the University of Stockholm, Sweden. I organized and led sessions on nanosatellite systems engineering, with examples around the BIRDY-T and CURE projects.
- **Groupe de Recherche de Géodésie Spatiale (Space Geodesy Research Group) (GRGS) Summer School:** I participated in the 2016 edition in Aussois, with a presentation on the orbit determination technique of BIRDY-T, in a preliminary version of my thesis results.
- **Engineering Schools:** I have repeatedly mentored long-term projects on BIRDY-T in engineering schools (M1 or M2 levels) for ELISA (2013/14, 3 students), Centrale Lille (2013-2015 7 students, 2014-2016 7 students), and Centrale Paris (2014/15 10 students, 2015/16 3 students). The 2015 team from Centrale Lille was able to present its work<sup>10</sup> at the general assembly of the Association Planète Mars (French chapter of the *Mars Society*, of which I was an administrator), which maintained an enthusiasm for Martian themes in their school for a few years.

Finally, as I appreciate the special relationship that forms during internships, my educational contributions have mainly adopted this format. Since the inception of CENSUS, I have hosted 45 interns in space engineering, ground telecommunications, embedded electronics, or flight dynamics, on nanosatellite projects or CENSUS tools, directly supervised or co-supervised with my engineers. Since 2020, with Covid-19 having damaged this connection, we have instituted monthly presentations of internships within the team, as rehearsals for future defenses, as well as listing on a CENSUS “wall of fame” upon each departure of an

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<sup>10</sup><https://planete-mars.com/le-projet-de-cubesat-birdy/>, 03/18/2015



## Remerciements à nos Prédécesseurs




### M1 Cindy LAMBERT, 03/2024, 5 mois

CENSUS, le pôle spatial de PSL Université Paris, hébergé à l'Observatoire de Paris, a été inauguré le 25/06/2018 par Alain FUCHS, président de PSL. Depuis le 1/01/2021, CENSUS est dirigé par :

- ★DR Coralie NEINER, stratégie
- ★Pr. Benoît MOSSER, pédagogie
- ★Dr. Boris SEGRET, technique

**Projets Accompagnés :**

- ★BIRDY, 2013
- ★QBDDIM, 2015
- ★BIRDY-T, 2018+
- ★CASSTOR, 2020+
- ★CIRCUS, 2013+
- ★COSMOCAL, 2022+
- ★CosmOrbitrap, 2013
- ★GAMA, 2021+
- ★GPU4SPACE, 2013
- ★CURE, 2018
- ★METEORIX, 2013+
- ★NANOPOT, 2015
- ★NOIRE, 2015+
- ★OGMS-SA, 2013+
- ★PICSAT, 2016
- ★SERB, 2013
- ★TERACUBE, 2019+

**Pôle spatial CENSUS**

- ★A.Eng. Kirill ANOHIN, 12/2023, 13 mois
- ★M2 Thuy Linh LA, 11/2023, 6 mois
- ★M.Eng. Pedro da FONSECA, 11/2023, 13 mois
- ★M2+M.Eng. Feliu LACREU, 10/2023, 19 mois
- ★M1 Elias MAZMOUZ, 08/2023, 3 mois
- ★DUT/L2 Alpha Mamadou DIALLO, 07/2023, 3 mois
- ★DUT/L2 Maimouna DIOP, 07/2023, 3 mois
- ★M2 Mohamed MANSOURI, 10/2022, 6 mois
- ★L3 Yanis GOUGEAT, 08/2022, 5 mois
- ★DUT/L2 Aoussetou KEITA, 07/2022, 3 mois
- ★M.Eng. Rashika JAIN, 03/2022, 2 ans
- ★M1 Augustin DECOCQ, 01/2022, 4 mois
- ★M2 Harshul SHARMA, 09/2021, 6 mois
- ★M1 Thomas LE VARLET, 09/2021, 9 mois
- ★M2 Silla S. DJIBRIL DRAMANE, 08/2021, 6 mois
- ★M2 Erwan ROUILLE, 08/2021, 6 mois
- ★M1 Julien BOUET, 06/2021, 5 mois
- ★M1 Youssoupha DIAW, 06/2021, 5 mois
- ★M2 Léa LARRIVET, 04/2021, 6 mois

**Pôle spatial C'ERES, jusqu'à 2020**

- ★DR Pierre DROSSART, 12/2020, 7 ans
- ★M2+MSc. Grégoire HENRY, 12/2020, 9 mois
- ★M.Eng. Thibault DELRIEU, 12/2020, 3 mois
- ★M.Eng. Louis LE LEUCH, 12/2020, 3 mois
- ★M2 Yoshimi CHAUVEL, 12/2020, 6 mois
- ★M2 Lancelot LE GUERN, 08/2020, 6 mois
- ★M1 Karim ABD EL DAYEM, 08/2020, 4 mois

- ★M2 Tim GLASIUS, 08/2020, 6 mois
- ★M1 Essaid TIGUERCHA, 08/2020, 3 mois
- ★M.Eng. Janis DALBINS, 11/2019, 1 mois
- ★M.Eng. Sébastien DURAND, 09/2019, 2 ans
- ★M2 Rashika JAIN, 09/2019, 6 mois
- ★M2 Roxane MORICE, 09/2019, 6 mois
- ★Dr. Gary QUINSAC, 08/2019, 4 ans
- ★M2 Claire CASTELL, 08/2019, 6 mois
- ★BTS Jonathan LUU, 08/2019, 4 mois
- ★M1 Jean-Baptiste JARNOUX, 08/2019, 4 mois

**Equipe CCERES, jusqu'à 2018**

- ★M2 Balaji Viswanathan, 10/2018, 6 mois
- ★M2 Laetitia LEBEC, 09/2018, 6 mois
- ★M1 Aurore BOINEAU, 09/2018, 2 mois
- ★MSc. The « Huynh » HOANG, 04/2018, 3 mois
- ★M2 Jimmy FOUQUART, 02/2018, 6 mois
- ★M2 Florian JOUSSAUME, 09/2017, 6 mois
- ★M1 Nicolas BOCHARD, 09/2017, 4 mois
- ★M1 Guillaume THEBAULT, 08/2017, 4 mois
- ★M2 Tobias FLECHT, 08/2016, 6 mois
- ★M2+MSc. Nima TRAORE, 08/2016, 7 mois
- ★MSc. Chia-Ling « Adeline » LIANG, 07/2016, 5 mois
- ★M1 Zacharie BARROU DUMONT, 07/2016, 2 mois
- ★M1 Thomas GASCARD, 09/2016, 4 mois

**LabEx ESEP, jusqu'à 2015**

- ★M2 Jordan DIBY, 11/2015, 6 mois
- ★M1 Hao-Chih « Jim » LIN, 10/2015, 4 mois
- ★M1 Sébastien DURAND, 08/2014, 4 mois

Figure 5.16: CENSUS Wall of Fame, including the names of interns from L2 to M2.

intern or hire, with the departing individual receiving their own copy. Thus, the names of interns, from L2 to M2, are summarized for posterity, alongside those of professionals who have passed through CENSUS: the latest edition of the “wall of fame” is shown in figure 5.16 (list also in the appendix). This list does not include the many students hosted by CENSUS, several dozen, during supervised or mentored project modules, nor the interns from NCKU in Taiwan for BIRDY-T.



## 6.1 The “network”

### 6.1.1 Academic network

There is no need to detail how excellent we are, in France, at complicating and branching out our organizations, but perhaps this is the key to sustaining our actions. We saw in chapter 3 that even abroad, funding solutions have taken time to establish, except for student projects.

CENSUS’ role in the community has been crucial since its inception, driven by Pierre Drossart, who called for a forum dedicated to scientific nanosatellites under the aegis of CNES. This forum took place on April 1, 2015, and brought together the scientific community at CNES headquarters in Paris. It really initiated discussions, revealing the inadequacy of student nanosatellites and leading to CNES support for (notably) BIRDY-T, which I presented on this occasion with Daniel Hestroffer through funding from a Call for Research Proposals (APR) and NOIRE with a PASO/CNES study selection, in which I participated in support of Baptiste Cecconi.

When Coralie Neiner took over CENSUS in 2020, her efforts continued those of Pierre Drossart to convince CNES to open a specific “ticket-office” for scientific nanosatellites. She also created, on January 1, 2023, the CNRS Nanosatellites Research Federation, first in the region of Paris, and worked to secure the PSL budget into a multi-annual contract (instead of the annual contract which proved to be a management nightmare). As we have seen, these contracts have enabled hires and internships. These actions have given CENSUS strong momentum and good visibility.

My role has naturally been to support the federation alongside C. Neiner since I was elected to its scientific committee. I have taken charge of certain mutualization actions (sharing nanosat subsystems, electronic means, test techniques and ground segments). However, the inertia of these transversal structures requires more perspective to make an assessment, and we are only at the very beginning. One action of the federation, in which I participated during its first workshop in 2024, was to prepare a contribution for the CNES-INSU 2024 prospective workshop, expressing the Federation’s expectations for a dedicated funding office.

On a more technical level, my role in the community for the emergence of astrophysics nanosatellites has taken various forms:

- I established very early a nanosat systems and tools lending solution that allowed several projects to experiment with such systems. For example, for the OGMS-SA project of LISA, an inertia wheel and air-cushion platform set.
- I have regularly participated in the *iCubeSat*, *Interplanetary CubeSat Workshop*, since

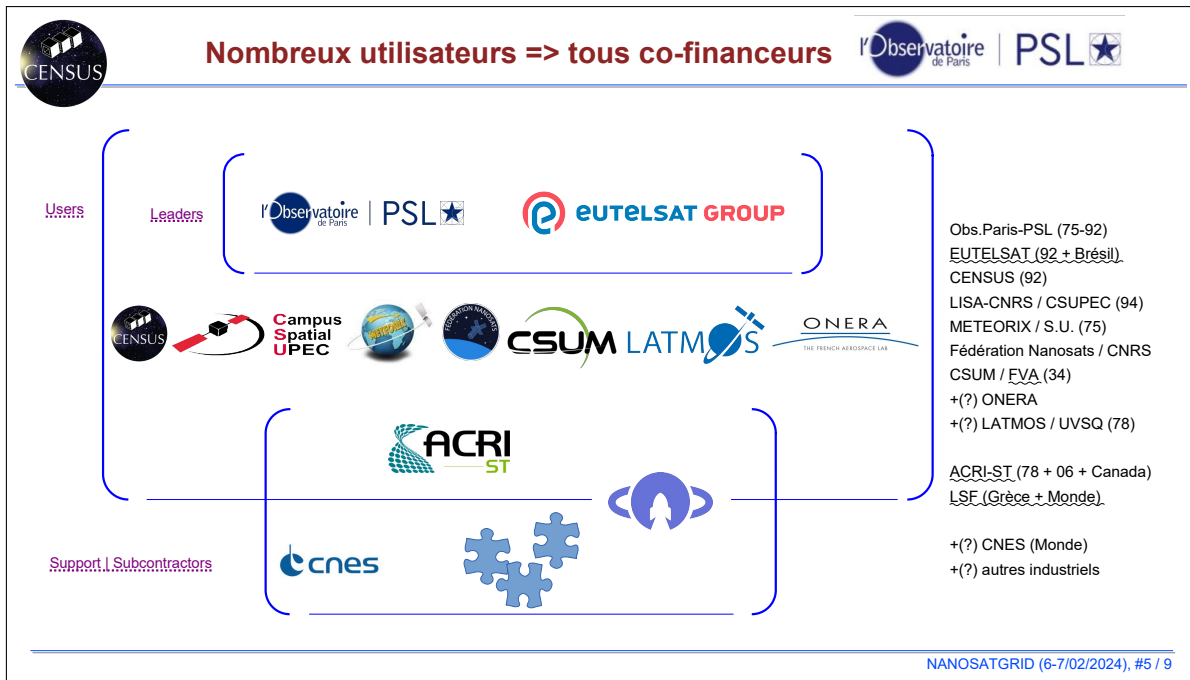


Figure 6.1: Example of industrial outreach, initial NANOSATGRID consortium.

the first edition in 2012 at M.I.T. in Boston, and then proposed to host it in Paris in 2018<sup>1</sup>.

- I have been part of 4 nanosatellite review committees:
  - In 2015, occasionally, for a preliminary design review of the IgoSat project at the University of Paris Cité,
  - For the PICSAT nanosatellite from LESIA, which was launched in 2018,
  - In 2019, occasionally, for a preliminary design review of the SCION-X project from NCU, Taiwan,
  - For the CROCUS nanosatellite from ONERA, whose preliminary design review was held in 2023.

Finally, but this is also an action in its infancy without sufficient hindsight, the “Île-de-France Space Academy” brings together some major universities in the region. It was created in 2023 with a budget of €20 million over 5 years. It aims to establish a new training offer that gives significant importance to *NewSpace*. My contribution mainly involves creating a teaching module derived from our “PSL Week” offer (presented in § 6.3), for the benefit of academic programs and continuing education: it will involve using the PROMESS platform and our concurrent engineering methods, sometimes in coordination with modules from other universities, if possible starting from the 2024 academic year. This should lead to the funding of a “Platform Engineer” position at CENSUS, in coordination with the UFE.

### 6.1.2 Industrial network

Regarding the industry, several actions have been undertaken with varying degrees of success, as astrophysics is difficult to “valorize” (as they say) in a Business Model and for a target

<sup>1</sup><https://icubesat.org/archive/2018-2/icubesat-program-2018/>

market. However, we do our best to engage collaborations with the industry, which is mainly my responsibility. It is useful to mention here a few lessons we have learned:

- The promising French start-up GAMA approached us early on with its solar sail technology (I supervised one of their engineers during Covid-19). We rented out our clean room for them to test their sail folding procedure. They launched their first satellite in early 2023. We could have assisted them with their mission profiles, flight dynamics, and scientific cases, in addition to test and integration facilities. Unfortunately, our response time (due to a lack of legal personnel) to establish contracts eventually discouraged the leaders. Postponed?
- EUTELSAT GROUP, a major telecommunications satellite operator, offered secondary payload slots on its future satellites. We quickly found common interests in nanosatellites. Thus, we now jointly apply for funding for AbC (thesis), NANOSATGRID (equipment), the restoration of an 18m ground antenna, or a flight opportunity for COSMOCAL. The first lesson that emerges here is that patience is key!
- ACRI-ST, as early as 2022, applied alongside us for a preliminary version of NANOSATGRID, later expanded to a full consortium (Fig. 6.1). Their contribution to the antenna network is an undeniable added value to the project, though it is not yet funded.
- For this same NANOSATGRID project, the non-profit organization LIBRE SPACE FOUNDATION (Greece) co-applied with co-financing, THE QT COMPANY (Finland) co-applied without co-financing for interfaces and GMV (Spain) quoted a contribution for the orchestrator and centralizer software layers.
- On the topic of orbit determination, a collaboration attempt is underway with the company D-FINE GMBH (Germany) to study the interest of an embedded “artificial intelligence” that would optimize the choice of observation targets for navigation, thus saving significant system budget in attitude control.
- With the kind permission of the VAN ALLEN FOUNDATION, we reached an audience of entrepreneurs by hosting their “Partners Club” in 2024. This is a new kind of attempt that could bring us some industrial contacts.

There have been other attempts, and we will continue, but it must be remembered that our fundamental mission of knowledge dissemination is at odds with utilitarianism, “business confidentiality”, or the principle of patents (for example, PhD students *must* publish). The funders’ injunctions to bring us closer to the so-called “real” economy, since we are supposedly not part of it, are compounded by a habit of fractioning or truncating the requested funding: thus, I find it counterproductive (an understatement) to fund half-theses, as we will have to find another funding office to complete them, or to grant only 80% of a budget requested by a project that was organized and presented with a view to 100% funding... These “programmatic” aspects are perfectly appropriate in an HDR manuscript, as scientific action is constrained, even hindered, by the amount of time spent on funding requests and innovation attempts — therefore short-term and competing with R&T.

## 6.2 Conferences

Our network within the international community was primarily established through conferences. Interpersonal connections have always been fundamental to me, even if it means presenting a negative carbon footprint, which should therefore be compensated by turning it into concrete collaborations. In this regard, I do not mention here all the conferences I have attended, but only those that, I believe, play a structuring role for CENSUS:

- IEEE AEROSPACE<sup>2</sup>, Big Sky, Montana/USA: perhaps due to geographic isolation, this conference has been conducive to establishing relationships around cutting-edge concepts such as asteroid exploration with nanosatellites or flight dynamics tools. Unfortunately, inflation in the United States has placed the cost of this conference above the per diem.
- SMALLSAT CONFERENCE<sup>3</sup>, Logan, Utah/USA: becoming an annual event, it allows me to maintain connections from year to year with industry professionals, though it does not really create new contacts, despite initially easy relationships. For example, with E. Rouillé, for NOIRE, we expanded our reflections with American teams.
- SECESA<sup>4</sup>, traveling: organized every two years by ESA and CNES, it brings together a community of systems engineers around concurrent engineering methods and tools; I developed the connection with the CNES PASO team around its IDM-CIC and VTS tools, notably to provide user feedback to the developer SPACEBEL or to consider alternatives to the proprietary software MS-EXCEL.
- ISSFD<sup>5</sup>, traveling: this is also a biennial event that allows monitoring of flight dynamics discussions, in a rather friendly format for establishing relationships among experts; it is also an opportunity for peer-reviewed publications that serve as references, and I have presented several of my autonomous optical navigation works there.
- OSCW<sup>6</sup>, traveling: initially organized by a team of engineers from ESA/ESOC, there have been several editions at which CENSUS has regularly presented the open-source tool DOCKS and our MBSE approach; it was also in this context that a rapprochement with the *Libre Space Foundation* was made to support NANOSATGRID.
- ICUBESAT<sup>7</sup>, traveling: already mentioned as I hosted it in 2018 in Paris under the aegis of LabEx ESEP, it played an important role in the 2010s for Deep Space thinking, and I regularly presented projects there; unfortunately, it was very early on faced with competition and then canceled during Covid-19, with the risk of not continuing.

Finally, more general periodic conferences (such as IEEE Aerospace, by the way) have been opportunities to establish contacts for potential collaborations, such as 4S, IAC, and ESA Industry Days with *Politecnico di Milano* or the South African company SIMERA SENSE for optical navigation and AbC.

## 6.3 Outreach

### 6.3.1 PSL Week and PSL FabLabs

The most academic of my outreach actions is the “PSL Week”. PSL University invites all its students to explore other disciplines through a week-long immersion in its various institutions. This week counts towards their curriculum as a week of study. I proposed a contribution in the form of a concurrent engineering campaign, for which I designed a scenario adapted to the expected technical levels. This “educational product” has then served as a basis for the contributions I made to the Île-de-France Space Academy (Cf. § 5.3).

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<sup>2</sup><https://www.aeroconf.org/>

<sup>3</sup><https://smallsat.org/>

<sup>4</sup>Systems & Concurrent Engineering for Space Applications, e.g., at ISU, Strasbourg, in 2024  
<https://technology.esa.int/event/secesa-conference-2024>

<sup>5</sup>International Symposium on Space-Flight Dynamics, <https://issfd.org/>

<sup>6</sup>Open Source CubeSat Workshop, <https://oscw.space>

<sup>7</sup>Interplanetary CubeSat Workshop, <https://icubesat.org/>





Figure 6.2: PSL Week 2022 conclusion poster (S. Cnudde, SIGAL/LESIA).

The scenario is derived from the CURE project for measuring the transit dates of exoplanets, potentially in preparation for the ESA ARIEL mission. For PSL Week, CURE is presented as a non-selected mission but for which a new version could be adopted, called “mCURE”, lighter and more targeted, limited to 10 high-value exoplanets. Participants form two teams and learn what it is like to define a space mission. They must design a realistic mission profile and a development plan that ensures the successful observation of all 10 exoplanets.

Two editions have already taken place, in 2022 (Fig. 6.2) and 2024, as well as a first half-day session for schools (2023).

In addition to “PSL Week”, developing links around the “PSL FabLabs” theme allowed me to discover in 2023 other PSL entities and, by extension, the disciplines of École Nationale Supérieure des Arts Décoratifs, PSL (ENSAD) which has significant manufacturing resources (and a FabLab) for various materials. I gave a seminar there, and subsequently, a first artist residency was organized (late May 2024, hosting Olivain Porry). This is a new attempt to reach a professional circle different from ours, which, in turn, could relay the role of astrophysics to the general public in artistic contexts.

### 6.3.2 Nex’Orbiter

Passionate since 2009 about “ORBITER *Spaceflight Simulator*”<sup>8</sup>, created by Dr. Martin Schweiger in the early 2000s, I have long been contemplating a futuristic interplanetary navigation paradigm: the brachistochrone, which involves traveling with constant thrust,

<sup>8</sup>official site <http://orbit.medphys.ucl.ac.uk/>, presentation at ESA in 2006 [44]



Figure 6.3: “Nex’Orbiter” is a network game project based on the open-source space flight simulator ORBITER created by Dr. Martin Schweiger. (Credit: “Jia”, [jiaspace.pro](http://jiaspace.pro))

delivering, for example, 1 G of *prograde* acceleration for the first half of the journey and *retrograde* for the second half. Although no such continuous propulsion with this level of power currently exists, unfortunately, this concept would allow reducing a Earth-Mars trip to just a few days. ORBITER is a simulator that adheres to the rules of space flight dynamics, in an elegant 3D graphics engine. Based on this, it is possible to use ORBITER for a persistent, real-time networked universe: it is a playful approach to raise awareness of space exploration and the state of astrophysical knowledge, while stimulating political reflection on the future uses of space.

While I have been actively contributing since 2019, privately, to the ORBITER community on the development of a “network” feature, Martin Schweiger chose to release the code as open-source under the MIT license on 27/07/2021. I then resolutely directed my efforts towards a “networked video game” based on this simulator. Observing that the CUBESAT theme naturally lends itself to futuristic exploration thinking (auxiliary probes of a main vessel...), I presented this project to the Open Program of the Observatory of Paris-PSL in 2022. The observatory agreed to support the project and renewed its support in 2024.

Here is a personal project that has a foot in my professional sphere. It is now called “Nex’Orbiter” and is jointly led with my wife on the graphical aspects, scenario, and communication (Cf. Fig. 6.3 by Chia-Ling “Jia” Liang). We hope to establish a new bridge to scientific knowledge from the world of video games. With luck and a lot of work, the theme of astrophysical nanosatellites might also reach the public through the persistent universe of Nex’Orbiter.

### 6.3.3 Miscellaneous

My role as an administrator of the Planète Mars association (Cf. detailed CV), the French chapter of the *Mars Society*, has led me to give several public lectures in France on various manned Mars flight projects. I also contributed to the collective book of the association “Embarquement pour Mars”, prefaced by French astronaut Thomas Pesquet: I wrote the

chapter “Scientific Challenges” (at the time, in 2013). Subsequent editions followed, and I contributed to the first two, in 2013 and 2015.

In 2020, I wrote an informational article on scientific nanosatellites and our activities at CENSUS, for the participatory media “The Conversation France”: “Nanosatellites Also Enable Scientific Research”<sup>9</sup>.

Finally, I have been invited twice to Radio France. The first time was on France Inter as a member of Planète Mars, on the day of the arrival of the CURIOSITY/NASA rover in Mars’ Gale Crater on 6/08/2012<sup>10</sup>. The second time was on France Culture, on 9/05/2018, for a “4 minutes” segment on my PhD project in autonomous interplanetary navigation<sup>11</sup>.

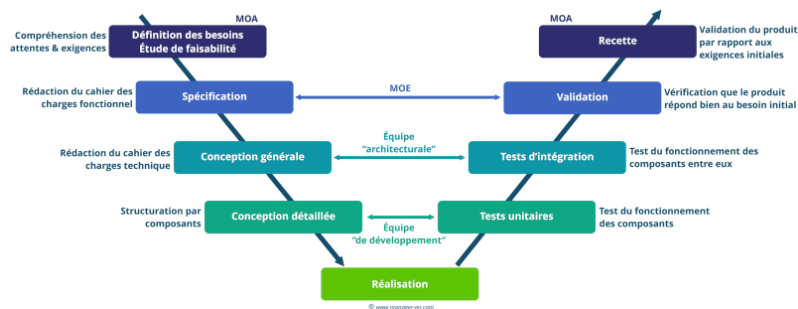
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<sup>9</sup><https://theconversation.com/les-nanosatellites-permettent-aussi-de-faire-de-la-science-136274>

<sup>10</sup><https://www.radiofrance.fr/franceinter/podcasts/on-verra-ca-demain/objectif-mars-2130111>

<sup>11</sup><https://www.radiofrance.fr/franceculture/podcasts/la-recherche-montre-en-main/navigation-autonome-pour-un-cubesat-interplanetaire-6331564>





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We still have a lot to do at CENSUS. If I had to extract priorities, I would mention four below that will shape my activities in the coming years.

## 1. Generalize MBSE and CI/CD

Guidelines are mentioned in § 5.2.4 that can already be detailed: maintaining MBSE modeling throughout the B/C/D/E phases, formalizing responses to this modeling, promoting the approach in conventional space, and even in other sectors.

The interest of system engineering, but also its difficulty, is staying up-to-date throughout the project. The MBSE approach is part of this and must leverage its appeal in phase 0/A. Since it concerns the mission execution and not the satellite design itself, its relevance appears less critical after the preliminary definition review. This is a mistake, as it can become strategic for arbitrating solutions to anticipated or unforeseen problems, defining and prioritizing test campaigns, subsystem acceptance tests, and in-flight commissioning: this is the upstream phase of the “V-cycle”. Indeed, CI/CD solutions (now applied to our DOCKS software, § 5.1) are particularly well-suited to the MBSE approach: developments can be tracked and archived like any code using a versioning tool, and, moreover, cumulative tests can be associated with it to monitor that scientific coverage remains assured. The goal for CENSUS will thus be to popularize both the MBSE approach, its CI/CD environment under *git+GitLab*, and its updating at each project review.

In the unscrupulous commercial world of *NewSpace*, the MBSE approach can regulate dialogue with subcontractors. It will not (or not for a long time) ensure flight operation. Even when purchasing a complete platform, at best the contract will ensure its proper functioning in the laboratory. Thus, the design of elementary tests by the client, or of complex functional

<sup>1</sup>“V-cycle”: it is difficult to attribute this diagram to anyone in particular; here it is borrowed from the online article by Rémi Lardilleux, dated 3/07/2023



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chains, can be inspired by the mission MBSE. In doing so, deliverables from the supplier can also be specified in the contract, such as a data set to be provided in response to a stimulus derived from the MBSE. The integration phase can then begin earlier and more effectively. Similarly, by inspiring flight operations well in advance, modeling will structure commissioning and thus its contractualization, particularly if this commissioning is entrusted (by naivety or obligation) to the chosen integrator for the platform. Of course, this is only a hope at this stage, but CENSUS will have several opportunities to propose such clauses to project teams.

Finally, the design of the PROMESS Plateau was intended from the beginning for use beyond just nanosatellites. It is tempting to use it to support a “proposal” for an instrument, even outside of *NewSpace*. The MBSE approach, focusing on the mission, would contribute to radically changing the tone of proposals submitted to space or funding agencies (ANR, Horizon..). It is also the methodological core for new training in system engineering. CENSUS will give seminars in this direction to promote such service offers in space, at CNRS, and towards companies. Another promotional factor, more technical, will be to seek interfaces with tools from “conventional MBSE”, meaning those targeting embedded code skeletons and UML diagrams. In particular, fluid interfaces with ESA’s OCTD, CNES’s IDM-CIC, and for the production of documentary structures will need to be explored.

It is also worth noting that the timing is favorable as the new Space Academy of Île-de-France has just approved CENSUS’ request for funding of 2 years, or more, for a “Plateau Engineer” position on our concurrent engineering work.

## 2. Adopt *Hardware-in-the-Loop*

*Hardware-in-the-Loop* makes perfect sense when systems are stimulated by mission modeling and the effects of the system are automatically utilized, for analyzing results or stimulating other systems.

The FLATSAT project plays an immediate role in elementary testing. Its logical evolution is to receive increasingly complex software layers to control the COTS that will be connected to it. The FLATSAT will thus become the natural link between the MBSE approach and the AIT/AIV phases.

The MBSE approach should translate into elementary tests and then into functional tests. Mission modeling will allow for extracting typical or “boundary domain flight” phases. These will be concatenated into a shortened but still real-time scenario. For example:

- To test a star tracker, after static characterization of light source avoidance angles (Sun, Moon, day limb, platform reflections), eclipse alternations and risks of stray light for the mission will be easily simulated. It is even possible to couple them with our one-axis rotation platform, which would support the star tracker, and a variable light source.
- Still with this one-axis rotation platform, it is possible to command an inertia wheel and check its saturation limits, in a scenario with frequent pointing variations.

Always via the FLATSAT, system reactions will be captured and utilized for analysis. The goal is then to re-inject them as inputs to the MBSE to verify if scientific observation conditions remain satisfied and, ultimately, if scientific coverage is impacted. For example, the star tracker may stop producing quaternions for a while, which will translate into a delay in establishing inertial pointings. Or, the inertia wheel might deliver a lower torque than expected, or even saturate, delaying the *slew* duration between two pointings.

An academic partner like *Politecnico di Milano* could teach us into *hardware-in-the-loop*, and in return, our expertise in astrometry could benefit them. These few examples already illustrate the necessity of complementing tests from a platform supplier with those conducted

by the scientific client of the platform. They do not necessarily require, or not all, heavy tooling. For some (and contractually), they could even be conducted directly at the supplier's site, which would add flexibility and reduce calendar risk.

### 3. Promote EMC

The issue of Electromagnetic Compatibility (EMC) is critical for scientists, both in conduction and in radiation, particularly at low frequencies (e.g., the NOIRE project, Chap. 4.2). It is poorly covered by the industry and requires early iterations between the client and suppliers. As noted in §5.2.4, it is also poorly covered by CENSUS, and a collaboration with ARIANEGROUP will indeed be initiated in 09/2024 on this topic: the CNRS Nanosats research federation has just agreed to fund an electronics engineer position at CENSUS for the federation's generic needs, which explicitly includes this EMC study.

The topic is even more delicate in *NewSpace* because the philosophy of COTS does not foresee re-design of subsystems. Therefore, it is necessary to “promote” EMC even though it is rarely a commercial issue. Our efforts will aim to partner with integrators who are most concerned, at least for conduction EMC which creates unwanted functional couplings. In this regard, ARIANEGROUP is in the same position as our nanosatellite integrators, and its arguments will be valuable in pushing for change.

Regardless, we will need to specify and test EMC. The original methods from ARIANEGROUP are promising: they combine “simple” requests for measurements from the supplier and a contribution to “our” modeling. They can be considered in the pre-bid consultation phase, then as deliverables for a preliminary milestone, before confirming the actual order of a subsystem. Without prejudging the solutions that would be technically feasible based on the results, it does not seem too optimistic to hope to include (and fund) these additional steps in procurement contracts, especially since they represent added value and recognition for the supplier.

### 4. Enhance DOCKS for Continuous Propulsion

The open-source DOCKS software suite is still not widely known. Yet, despite the existence of other free solutions, such as GMAT or TUDat, its originality is real: the “propagators” are technically essential and give the tool its legitimacy. But other modules, such as visibility, pointing, power, data, etc., are crucial for structuring any mission and are generic. It is necessary to further enhance DOCKS with additional functions, for example, to integrate coupling with ADCS simulations (through ongoing collaboration with our colleagues in Brazil), with EMC, or to assess key thermo-mechanical constraints without resorting to heavy tools at the project's start.

Continuous propulsion is typical of *NewSpace* (including cold gas solutions). It is a priority for enhancing DOCKS. It will likely become standard in nanosatellites, whether for deorbiting, orbital positioning, and in *deep space*, for proximity operations or even cruise. Its implementation was initiated in DOCKS in 2020. With the propagator now robust, it is possible to continue this development by associating it with specific propulsion strategies. Indeed, it is not enough to introduce a new component into the propagation calculation itself; we need to offer the user propulsion strategies that combine active phases and pointing. This will lead us to increase our expertise in flight dynamics and, with the obligation becoming an opportunity, pave the way for a “trajectory solver”, a natural evolution of a good propagator.

Finally, we need to build a user community, with *install parties* online for DOCKS, technical webinars, and interfaces with agency tools (OCDT at ESA, IDM-CIC and STELA at CNES). Indeed, the arrival of a Plateau engineer will enable us to develop both the functions and our community.



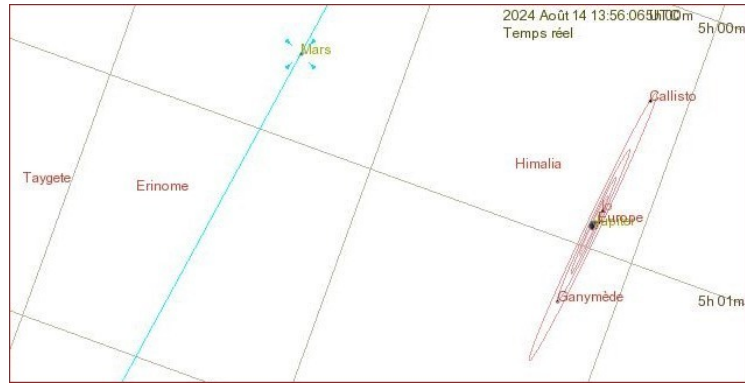


Figure 7.1: *Conjunction of Mars and Jupiter on 08/14/2024 (Celestia modeling)*

## In Conclusion

This thesis focuses on astrophysics, still poorly served by *NewSpace*. Nevertheless, through the upskilling of our community, I hope we will contribute to advancing *NewSpace* as well as other sectors, both industrial and scientific. I first think of extreme environments with robotics for deep-sea, extremophiles, or nuclear sites, for example, unless these sectors teach us instead. Exchanges will only be enriching.

One should not underestimate the level of reflection needed to develop these skills. This involves instrumental research and engineering sciences: system engineering, embedded electronics with COTS, and astrophysics at the nanosatellite scale. That is why, with Professor Benoît Mosser, we propose a *NewSpace* chair within the framework of the new Space Academy Île-de-France, which will fund post-doctoral contracts and “scientific residencies” on these topics over the next 4 years.

Certainly, constraints remain, notably the ideology of innovation against research or, simply, the trend towards “all-tools” and the inertia of support functions in the public sector. But there also seems to be a convergence of planets for CENSUS in 2024: Mars will be at  $\sim 15$  arc seconds from Jupiter on August 14, and then we will have 3 engineering positions at the start of the school year, a PhD obtained on AbC (and a response still awaited for an additional engineer), and a post-doctorate thanks to the *NewSpace* chair. Let’s now hope for funding for our scientific CubeSats!

# Appendix



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## The PhD Students (co-supervision)

Co-encadrement de Erwan ROUILLÉ, directeur de thèse B. Cecconi, “*NOIRE: a distributed radio imager in space*”, 2021-(en cours)

Co-encadrement de Janis DALBINS à/c 2020, avec A. Slavinskis, thèse dirigée par M. Noorma à l’Observatoire de Tartu (Estonie), “*Telecom experiments for deep space exploration with nanosatellites*”, 2016-2024

Co-encadrement de The Huynh HOANG, directeur de thèse B. Mosser, outillage de test du contrôle d’attitude nanosatellite, 2016-2017 (interrompue)

Gary QUINSAC, directeur de thèse B. Mosser, “*From Commercial-Off-The-Shelf to expected propulsion in nanosatellites*”, 2015-2019

## The Engineers

En tant que directeur technique de CENSUS, j’ai encadré les ingénieure et ingénieurs suivants:

Janis DALBINS (IR, 1+ an, en cours)

Kirill ANOHIN (AI, 2022-2023, 13 mois)

Pedro da FONSECA (IE, 2022-2023, 13 mois)

Feliu LACREU (IE, 2022-2023, 13 mois)

Rashika JAIN (IE, 2020-2022, 2 ans)

Grégoire HENRY (IE, 2020, 3 mois)

Thibault DELRIEU (IE, 2020, 3 mois)

Louis LE LEUCH (IE, 2020, 3 mois)

Sébastien DURAND (IE, 2017-2019, 2 ans)

## The Interns

M2 Kirill ANOHIN, 07/2024, 6 mois

M1 Guillaume BACHELIER, 06/2024, 6 mois

M2 Tomàs NUNES, 04/2024, 6 mois

M1 Cindy LAMBERT \*, 03/2024, 5 mois

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M2 Thuy Linh LA, 11/2023, 6 mois  
M2 Feliu LACREU, 10/2023, 19 mois  
M1 Elias MAZMOUZ \*, 08/2023, 3 mois  
DUT/L2 Alpha Mamadou DIALLO \*, 07/2023, 3 mois  
DUT/L2 Maimouna DIOP \*, 07/2023, 3 mois  
M2 Mohamed MANSOURI, 10/2022, 6 mois  
L3 Yanis GOUGEAT, 08/2022, 5 mois  
DUT/L2 Aoussetou KEITA \*, 07/2022, 3 mois  
M1 Augustin DECOCQ, 01/2022, 4 mois  
M2 Harshul SHARMA \*, 09/2021, 6 mois  
M1 Thomas LE VARLET, 09/2021, 9 mois  
M2 Silla S. DJIBRIL DRAMANE, 08/2021, 6 mois  
M2 Erwan ROUILLE, 08/2021, 6 mois  
M1 Julien BOUET, 06/2021, 5 mois  
M1 Youssoupha DIAW, 06/2021, 5 mois  
M2 Léa LARRIVET, 04/2021, 6 mois  
M2 Grégoire HENRY, 12/2020, 9 mois  
M2 Yoshimi CHAUVEL, 12/2020, 6 mois  
M2 Lancelot LE GUERN, 08/2020, 6 mois  
M1 Karim ABD EL DAYEM, 08/2020, 4 mois  
M2 Tim GLASIUS, 08/2020, 6 mois  
M1 Essaid TIGUERCHA, 08/2020, 3 mois  
M2 Rashika JAIN, 09/2019, 6 mois  
M2 Roxane MORICE \*, 09/2019, 6 mois  
M2 Claire CASTELL, 08/2019, 6 mois  
BTS Jonathan LUU \*, 08/2019, 4 mois  
M1 Jean-Baptiste JARNOUX, 08/2019, 4 mois  
M2 Balaji VISWANATHAN \*, 10/2018, 6 mois  
M2 Laetitia LEBEC, 09/2018, 6 mois  
M1 Aurore BOINEAU, 09/2018, 2 mois  
M2 Jimmy FOUQUART, 02/2018, 6 mois  
M2 Florian JOUSSAUME, 09/2017, 6 mois  
M1 Nicolas BOCHARD, 09/2017, 4 mois  
M1 Guillaume THEBAULT, 08/2017, 4 mois  
M2 Tobias FLECHT \*, 08/2016, 6 mois  
M2+MEng. Nima TRAORE, 08/2016, 7 mois  
M1 Zacharie BARROU DUMONT, 07/2016, 2 mois  
M1 Thomas GASCARD, 09/2016, 4 mois  
M2 Jordan DIBY, 11/2015, 6 mois  
M1 Hao-Chih « Jim » LIN, 10/2015, 4 mois  
M1 Sébastien DURAND, 08/2014, 4 mois

\* : *co-encadrement*

## Projects

Chef de projet de **NANOSATGRID**: interconnexion de segments sols d'opérations nano-satellites (2022+)

Chef de projet de **BIRDY** (2013+):

- BIRDY: projet de CubeSat interplanétaire pour mesures de radiation entre Terre et Mars
- QBDIM: projet de CubeSat interplanétaire en mission d'accompagnement à un astéroïde
- BIRDY-T, fusion de BIRDY et QBDIM

Chef de projet de **AbC** (2020+): Algorithme d'astrométrie embarquée pour nanosatellite

Chef de projet de **NOIRE** (2021+): Essaim de nanosatellites de radio-astronomie en orbite lunaire

Chef de projet de **Nex'Orbiter** (2020+): Jeu en réseau de navigation interplanétaire sur simulateur open-source

Chef de projet de **DOCKS** (2015+): Suite logicielle open-source de prototypage de mission nanosatellite

Chef de projet de **PROMESS** (2016-2017): Plateau d'ingénierie concourante au bâtiment 15 du site de Meudon de l'Observatoire de Paris-PSL

Co-encadrement des projets VEGA (salle blanche, 2017-2018), FLATSAT (outillage de tests électroniques à distance, 2022+)

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## Publications & Scientific Communications

### Articles, Proceedings, Posters

*(publications en auteur ou co-auteur)*

6th ESA Industry Days, Delft (Pays-Bas), 09/2023, Poster : « AbC, an ADCS Commissioning Service », Pedro da Fonseca & al.

mm Universe 2023, Grenoble, 06/2023, Proc.: “The COSMOCal project and its prototype in the 1 mm band” , Alessia Ritacco & al.

MDPI Aerospace 2023, PAPER

Dalbins, J. & al."Interplanetary Student Nanospacecraft: Development of the LEO Demonstrator ESTCube-2". Aerospace 2023, 10, 503. doi:10.3390/aerospace10060503

SmallSat 2022, PAPER

B. Segret, S. Bammens, S. Bras, D. Marszk, V. Shiradhonkar, V. Zelenevskiy, D. Evan, “On-board images to characterize a CubeSat’s ADCS”, SSC22-VI-06, 36th Annual Small Satellite Conference, Logan (Utah/USA), 08/2022

4S 2022, PAPER

B. Segret, S. Bammens, S. Bras, D. Marszk, V. Shiradhonkar, V. Zelenevskiy, D. Evan, "On-Board images to specify and commission the ADCS," The 4S Symposium 05/2022, Vilamoura (Portugal)

4S 2022, Small Satellite System and Services, Vilamoura (Portugal), 05/2022, Poster: “A radio-source tracker: An adaptation of the star tracker technique to satellite swarm radio interferometer”, Erwan Rouillé & al.

IEEE 2022, PAPER

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IEEE 2022 PAPER

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## RÉSUMÉ

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Le “NewSpace” est formidable. Connue pour ses méga-constellations de nanosatellites autour du globe, la surveillance en continu des incendies, le repérage de navires illégaux ou bientôt l'échange de clés cryptées. C'est donc un foyer d'innovations avec de belles opportunités de financement. Mais l'astrophysique, dont l'importance politique ne se dément pas dans l'ère moderne, reste le parent pauvre de ce changement de paradigme, faute de débouchés commerciaux immédiats. Pourtant, je suis convaincu qu'il faut encore et toujours monter en compétences dans ce domaine pour que les décisions de financement s'imposent naturellement. Ce mémoire pour demander l'habilitation à diriger des recherches est donc un acte politiquement engagé. J'y exposerai mon expérience industrielle et mon arrivée dans le spatial scientifique, qui coïncide avec le lancement du premier nanosatellite français en 2012, se poursuit avec les premiers CubeSats interplanétaires en 2018 et, désormais, une première armada vers la Lune et l'astéroïde double Didymos. Il y a fort à parier que toutes les missions d'exploration offriront désormais des opportunités pour des nanosatellites, donc aussi des opportunités de développements technologiques rapides pour les équipes de recherche en astrophysique. Avec mes mentors Pierre Drossart et Jean-Pierre Lebreton dans les années 2015, nous avons fait ce pari et choisi d'investir à long terme sur les nouvelles compétences requises pour des nanosatellites de qualité scientifique, car un “CubeSat” est loin d'être un satellite en kit: il fallait des méthodes, des outils et des équipements dédiés, autrement dit un écosystème, devenu bientôt pôle d'expertise de l'Observatoire de Paris - PSL. Cet environnement m'a permis de co-encadrer 4 doctorants, 9 ingénieurs et 45 étudiants en stages de fin d'études de DUT ou de Master. J'y ai conçu un support d'ingénierie original, au profit de plus de 7 équipes de recherche sur leur projet de nanosatellite scientifique. J'y ai mis en place quelques partenariats avec l'industrie. L'intérêt d'une HDR est donc, pour moi désormais, de promouvoir les spécificités des nanosatellites pour l'astrophysique, et ceci aux plus hauts niveaux académiques, afin que les ingénieurs et docteurs ainsi formés produisent à leur tour du Savoir et des savoir-faire.

## MOTS CLÉS

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ingénierie spatiale, espace profond, radio-astronomie, planétologie, cosmologie, physique stellaire, météo de l'espace, géodésie, interplanétaire, exploration spatiale, autonomie, nanosatellites, CubeSat

## ABSTRACT

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“NewSpace” is great. Known for its mega-constellations of nanosatellites around the globe, continuous monitoring of fires, tracking of illegal vessels and, soon, the exchange of encrypted keys. It's a hotbed of innovation, with excellent financing opportunities. But astrophysics, whose political importance is undeniable in the modern era, remains the poor cousin of this paradigm shift, due to a lack of immediate commercial outlets. And yet, I'm convinced that we still need to build up our skills in this field, so that funding decisions can be taken as a matter of course. This dissertation is therefore a politically committed act. In it, I will describe my industrial experience and my arrival in scientific space, which coincides with the launch of the first French nanosatellite in 2012, continues with the first interplanetary CubeSats in 2018 and, now, a first armada to the Moon and the double asteroid Didymos. It's a safe bet that all exploration missions from now on will offer opportunities for nanosatellites, and therefore also opportunities for rapid technological developments for astrophysics research teams. With my mentors Pierre Drossart and Jean-Pierre Lebreton in 2015, we took this gamble and chose to make a long-term investment in the new skills required for scientific-quality nanosatellites, because a “CubeSat” is far from being a kit satellite: dedicated methods, tools and equipment were required, in other words an ecosystem, which soon has become a center of expertise at Observatoire de Paris - PSL. This environment enabled me to co-supervise 4 PhD students, 9 engineers and 45 students in their final year of a BTS or Master's degree. I designed an original engineering support for more than 7 research teams on their scientific nanosatellite project. I also set up a number of partnerships with industry. For me, the purpose of an HDR is now to promote the specificities of nanosatellites for astrophysics, at the highest academic levels, so that the engineers and PhDs thus trained in turn produce knowledge and know-how.<sup>a</sup>

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<sup>a</sup>DeepL.com and ChatGPT/Openai were used to translate this document from French.

## KEYWORDS

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space engineering, Deep space, radio-astronomy, planetology, cosmologie, stellar physics, space weather, geodesy, interplanetary, space exploration, autonomy, nanosatellites, CubeSat