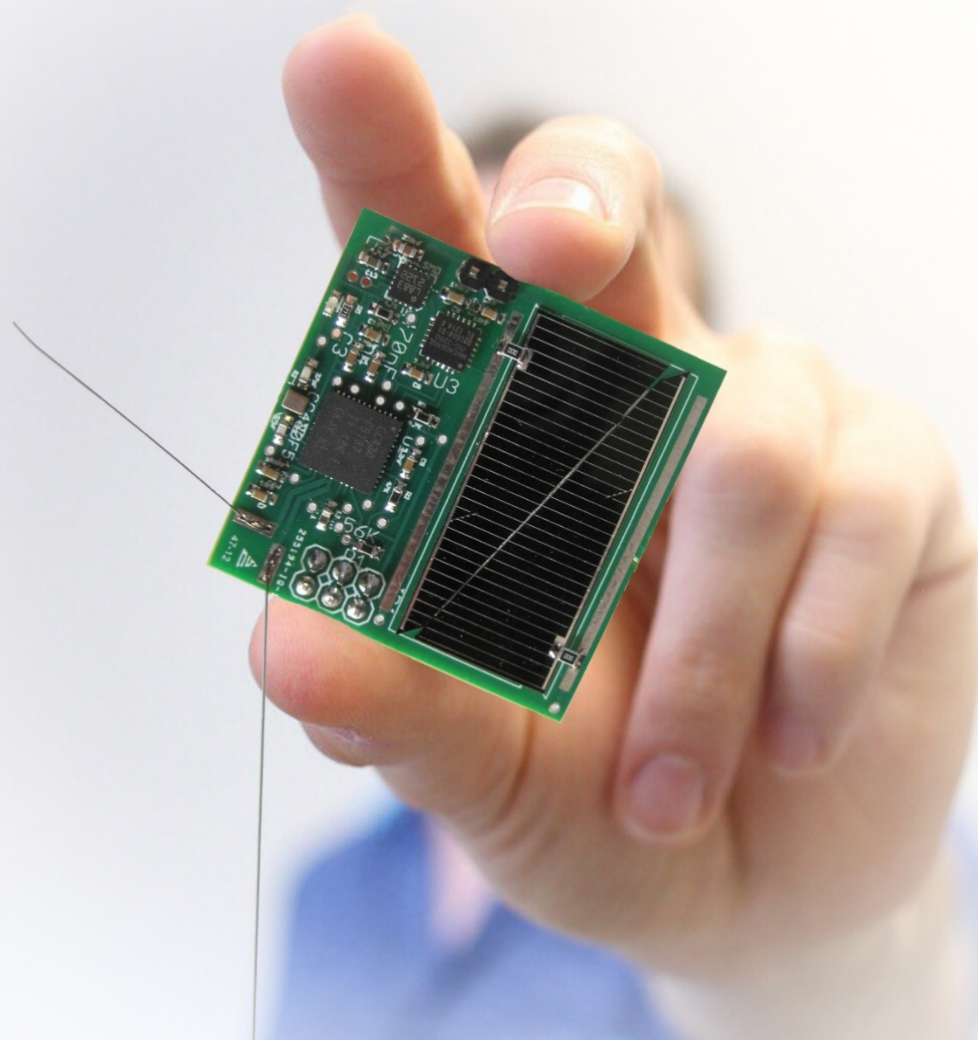
ChipSats: New Opportunities

FINAL REPORT



INTERNATIONAL SPACE UNIVERSITY

MSS20 - TEAM PROJECT

ChipSats: New Opportunities
Final Report

International Space University
MSS Program 2020

This MSS 2020 Team Project work was conducted at the ISU Strasbourg Central Campus in Illkirch-Graffenstaden, France.

The cover image is an original photograph by the ChipSat team. It represents the scale and mass of the 10 gram ChipSat satellite, belying the common misconception of satellites as massive platforms.

Image of the ChipSat courtesy of:

Allan, A., 2015. *NASA Approves Kicksat's Tiny DIY Satellites for Second Attempt*. [online] Available at: <https://makezine.com/2015/04/13/nasa-approves-kicksats-tiny-diy-satellites-second-attempt/> [Accessed 1 March 2020].

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Acknowledgements

The ChipSat Team Project team would like to acknowledge the faculty members of the International Space University who provided valuable feedback during the project. In particular, we would like to recognize our faculty supervisors, Professor Gongling Sun and Professor Taiwo Tejumola for their guidance and support.

Additionally, we would like to acknowledge all the individuals and organizations that dedicated their time and energy to participating in video conferences and responding to email queries. Consultation with industry was incredibly important for this project.

We would also like to thank all our families and friends for their continuous support and encouragement for the duration of the team project.

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Abstract

The consistent trend in the miniaturization of electrical and mechanical components has enabled a steady downscaling in satellite sizing. This evolution has progressed from traditional heavy spacecraft to CubeSats, and now to a new generation of satellites: ChipSats. The ChipSat, with a mass of fewer than 10 grams, demonstrates several features atypical to those found in traditional satellite design; a uniquely low platform mass, inexpensive fabrication methods, and augmented redundancies. The appropriate leverage and synergy of these features have the potential to drive the design envelope toward innovative mission architectures while lowering traditionally high barriers of entry to space. There is an opportunity for future mission designers, academic institutions, and space-aspiring entities alike to benefit. The International Space University has expressed interest in launching a ChipSat of its own within five years. This report states the benefits and anticipated challenges for pursuing this endeavor. The key elements concerning technical, educational, and legal aspects have been evaluated to inform the International Space University on a proposed path that must be navigated to ensure a successful ChipSat launch while adding value to the self-imposed institutional targets. The delivery of a ChipSat into space by the International Space University can serve as a model for other educational institutions to model after. Concerning interested space agencies and commercial entities, a set of mission profiles have been put forward to illuminate the relevant mission orchestrators on the potential mission concepts that ChipSats can support. Although the literature provides coverage across all the mission-relevant disciplines, there are outstanding gaps that demand attention. A series of recommended next-steps have been put forward to the key decision-makers to address the identified inadequacies. Ultimately, the value ChipSats may bring through the democratization of space, space education, and future mission design outweighs the hurdles that must be overcome.

Faculty Preface

The fundamental issues facing space missions today are their inherent high development costs and prolonged duration for achieving mission objectives. Resolving these problems has proven remarkably elusive until the introduction and applications of nano (1 - 10 kg) and pico (sub-1 kg) satellites that utilize untraditional risk-taking approaches to accomplish low costs and swift delivery. Chip-sized satellites (ChipSats) belong to this class of satellites. They are miniaturized spacecraft with a mass on the scale of grams with volumes as low as the dimensioning of a credit card or a small postage stamp.

This class of satellite would introduce a paradigm shift in spacecraft design and disrupt the space industry by lowering the barrier of entry to space and enable the development of radically different types of space missions. However, unlike the traditional satellite, the technical readiness level of ChipSat components and systems remain at an early stage. The chief focus of this Team Project was to carry out an interdisciplinary study of ChipSats, establishing the state-of-the-art in all relevant disciplines, and identify potential opportunities for future missions and applications in the technical and non-technical areas that several educational institutions can embark on using the International Space University as a model.

Keeping this in mind, we have had the honor to share the ideas and concepts with our international, intercultural, and interdisciplinary team of 21 graduate students from the MSS20 class who come from 18 countries. The ChipSat Team worked assiduously to analyze the current situation of ChipSat development, their typical application while also identifying the cultural, political, educational, scientific, legal, and economic rationales for future applications. This report outlines the cases of ChipSat applications which might be of interest to space agencies and commercial entities to evolve incrementally over time into something truly transformative. The paper also provides some recommendations to key decision-makers to address the identified inadequacies.

As the faculty interfaces and on behalf of all ISU faculty members, we would like to express our gratitude and thanks to all the team members for their sincere effort, commitment, hard work; and all our best wishes to the creative idea of ChipSat development and its application with a great future.

Prof. Gongling Sun and Dr. Tejumola Taiwo

Author Preface

Our working group is composed of 21 students from 18 different countries. Expertise encompasses engineering, law, communications, computer science, business and management, architecture, and science. Within the team, our level of work experience ranges from one to 30 years. With such a diversity and depth of talent, defining a common goal proved to be one of the most challenging aspects of the team project. Uniting behind a singular idea required the team to be dynamic and fluid in pushing the project boundaries and in our preconceptions.

Following the presentation of our team project challenge and defining the state-of-the-art for ChipSats through a literature review, the technological limitations could have easily thwarted a positive outcome. How would it be possible to forecast both current and future applications in the face of a technologically limited platform? The answer lay in the positioning of a human element as the driver of the project. Building an ISU ChipSat Roadmap provided the fundamental link between seemingly disparate elements: limited technological capabilities, democratizing space, extending STEM outreach, and mirroring ISU's development goals.

By shifting the focus away from how far the technology needed to adapt to become useful (though a careful and considered analysis of future missions is explored), the team instead looked at how to adapt expectations by making the current limitations capable of reaching a wider field. Developing and enhancing the ISU curriculum through a dedicated ChipSat technology program and connecting with those who have limited space experience and resources through small satellite symposiums and ChipSat programming competitions is at the core of our team project.

We believe the power of ChipSats does not rest in its technological prowess, but rather in its ability to ignite and unite our collective human interest in space.

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List of Acronyms

3Is	Interdisciplinary, International, and Intercultural
ADCS	Attitude Dynamic Control System
ANFR	Agence National des Fréquences
APP	Space Applications
BOM	Bill of Materials
CDR	Critical Design Review
CMOS	Complementary Metal-Oxide-Semiconductor
CMR-19	Conférence Mondiale des Radiocommunications 2019
CNES	Centre National D’Etudes Spatiales
COTS	Commercial-Off-The-Shelf
CPCE	Code des Postes et des Communications Electroniques (France)
CPU	Central Processing Unit
D3S	Distributed Space Weather Sensor System
DIY	Do-It-Yourself
EAR	Export Administration Regulations
EC	Council Regulation
ECAM	École Catholique d'Arts et Métiers

EDT	Electrodynamic Tether
EEE	Electrical, Electronic and Electromechanical
EFW	Electric Field and Wave
EIRP	Effective Isotropic Radiated Power
ELaNa	Educational Launch of Nanosatellites
EMC	Electromagnetic Compatibility
ENG	Space Engineering
ESA	European Space Agency
EU	European Union
FCC	Federal Communications Commission
FPGA	Field-Programmable Gate Array
GLEE	Great Lunar Expedition for Everyone
GSA	European GNSS Agency
HPS	Human Performance in Space
HUM	Space Humanities
IADC	Inter-Agency Space Debris Coordination Committee
IDE	Integrated Development Environment
IMU	Inertial Measurement Unit
IPC	Institute for Interconnecting and Packaging Electronic Circuits
ISIS	Innovative Solutions in Space
ISO	International Organization for Standardization
ISU	International Space University
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunication Union
KKV	Kinetic Kill Vehicle
LEO	Low Earth Orbit
LIAB	Liability Convention
LLO	Low Lunar Orbit
MGB	Space Management and Business
MIFR	Master International Frequency Register
MSS	Masters of Space Studies
MTCR	Missile Technology Control Regime
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
OBDH	On-Board Data Handling
OS	Operating System
OSCAR	Observing Systems Capability Analysis and Review Tool
OST	Outer Space Treaty
PCB	Printed Circuit Board
PDR	Preliminary Design Review
PEL	Space Policy, Economics and Law
PRN	Pseudo-Random Noise

PRR	Production Readiness Review
R&D	Research and Development
RAM	Random Access Memory
REG	Registration Convention
RF	Radio Frequency
RFI	Radio Frequency Interference
RR	Radio Regulations
SAA	South Atlantic Anomaly
SAR	Synthetic Aperture Radar
SCI	Space Sciences
SDR	System Design Review
SES	Société Européenne des Satellites
SNR	Signal-to-Noise Ratio
SRR	System Requirements Review
SSR	Software Specification Review
SSP	Space Studies Program
STEM	Science, Technology, Engineering and Mathematics
SWPC	Space Weather Prediction Center
TASC	Triangular Advanced Solar Cells
TEM	Transverse electromagnetic
TRL	Technology Readiness Level
TRR	Test Readiness Review
TTC	Telemetry, Tracking, and Command
TTN	The Things Network
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UNISEC	University Space Engineering Consortium
UV	Ultraviolet
WMO	World Meteorological Organization
WRC	World Radiocommunication Conference

Currency

All currency in this report is given in USD, unless stated otherwise.

1. Introduction

The impossible has never stood in the way of space progress. Human nature coalesces around solving difficult challenges, and many forms of electronics have followed a relentless drive toward complex miniaturization. From the early behemoths that first graced our atmosphere, to the pint-sized Mars InSight companion CubeSats, spacecraft have been shedding size and mass, all while retaining integral mission capabilities. In the mantra of Dan Goldin, developing new technologies that are "faster, better, cheaper" has driven technology and innovation onto ever smaller platforms, capable of achieving mission-critical objectives. Developed in less time, with less mass, and at a lower cost, access to space is changing in fundamental ways. Sputnik-1 weighed in at 83.6 kilograms and transmitted a simple beep; ChipSats are capable of the same demonstration at under 10 grams. But is smaller necessarily better?

ChipSats - New Opportunities is an International Space University (ISU) Master of Science in Space Studies Team Project tasked with providing cutting-edge analysis and future mission development using a postage-stamp-sized spacecraft. This current paradigm shift represents new space deployment opportunities both in terms of mission design and mission concepts. The miniaturization mantra is driving technological progression toward smaller spacecraft with bigger expectations. But the tradeoff in mass and volume imposes the highest constraints on technology readiness, challenging our expansive dreams with a miniaturized and limiting reality. Smaller may not necessarily be better, but the tradeoffs in cost and redundancy certainly are.

The challenge was to deliver an interdisciplinary study on ChipSats, encompassing a state-of-the-art profile and remaining relevant to ISU's seven identified disciplines, with an eye toward future missions, applications, and developments as a primary project focus. The team responded with a comprehensive technical review and Technology Readiness Level (TRL) analysis of available ChipSat Commercial Off-The-Shelf components (COTS) and relevant subsystems, including a quantitative analysis of both future technology developments and potential mission applications, serving both scientific and commercial interests. The report highlights key economic drivers in standardized manufacturing opportunities for components and the role of redundancy in swarm deployments to affect both mission costs and viability, thus capitalizing on the primary benefits of endorsing ChipSats for future missions.

Our secondary deliverable, to provide a roadmap for ISU to launch ChipSats within five years, was originally designed as a minor focus; however, after undertaking an intense two-month literature review uncovering the distinct advantages and disadvantages of ChipSat technology, the team unearthed a kindred spirit of our own, which illuminated a clear desire to provide ISU with a programmatic launch roadmap. The message is simple: the ChipSat team wants to give back, by establishing a means to provide a reciprocal opportunity to a program that has given each team member the platform to launch a new space career. As such, the ISU ChipSat Roadmap became our primary focus, bolstered by our technical knowledge of the existing ChipSat capability landscape.

The ChipSat Team has crafted a thorough interdisciplinary approach, meeting the criteria for inclusion of all eight identified the ISU disciplines as shown below in Figure 1.1.

Table 1.1. TP ChipSat alignment with ISU disciplines

MGB (Space Management and Business)	The report establishes business cases, identifying potential new technologies, mission parameters, and commercial partners through both future lunar communications missions to support the search for and mining of lunar ice and space weather impact forecasting mission selections It develops a framework of commercial partners eager to engage and participate in the ISU ChipSat Roadmap and development of sponsored outreach kits It investigates the democratization of access to space, and the opening up of opportunity to smaller markets
HPS (Human Performance in Space)	The report outlines future missions to sense radiation levels in both the Earth's atmosphere and on the Moon, in the hopes of mitigating exposure consequences to human habitation in deep space It suggests, supporting rover missions with communication links, as they explore untouched areas of the Moon, might inform the habitability demands of any future lunar settlement by helping to establish safer long-term living environments
PEL (Space Policy, Economics and Law)	The report carefully analyzes the existing legal framework and associated challenges, the current policy decrements for small satellite operations, documented a step-by-step approach to establishing ISU as a launch provider, including frequency allocation, registration and liability and acknowledging our full intent to comply with space debris mitigation criteria It articulates the single largest potential impact on future missions regarding the cost of development and leverage in redundancy with ChipSat missions
SCI (Space Sciences)	The report weighs the value of COTS materials against the expectation of radiation exposure, testing the limits of the spacecraft lifetime It also provides future mission profiles with primary and secondary objectives for space weather and heliophysics analysis through the deployment of ChipSat clusters, and the measurement of seismic geologic activity on the Moon's surface
APP (Space Applications)	The report examines future mission opportunities for ChipSats by providing communications and performing space weather sensing It also envisions the ISU ChipSat as a demonstrator of both basic navigation and communication, transmitted through amateur radio bands, and linking with educational outreach
ENG (Space Engineering)	The report conducts a comprehensive TRL study of COTS components and subsystems, including available prototyping and potential redundancies in the manufacturing of ChipSats, plus an exhaustive gap analysis with recommendations It carries out a thorough examination of future mission possibilities utilizing ChipSat technology which will require advancements in the subsystem components, particularly propulsion

	ISU internal development offers the opportunity for hands-on learning through mission planning, component development, assembly, and launch integration
HUM (Space Humanities)	The team discovered broad channels to engage society in our collective drive of opening space to all people, in all nations At the heart of our ISU outreach campaign is the desire to unite diverse populations with the challenge of space discovery through education in Science, Technology Engineering and Mathematics (STEM) disciplines. Space is big enough for everyone
3Is (Interdisciplinary, International, and Intercultural)	The team determined that our collective experiences are relevant for inclusion in the discipline objectives, as the group suffered both lows and highs throughout the process However, following open and honest conversations among the team members, at several key junctures, the team was able to pivot on the lows and realign the group dynamics during critical weeks of preparation This, the team agreed, is as important as our final delivered product, and reaffirms our team mission objectives outlined in our original mission statement

1.1 Mission Statement

The mission statement, as agreed by the ChipSat team, is as follows:

To envision innovative ChipSat applications which will inspire the space community, by analyzing technology and potential markets, and establishing a Roadmap for ISU to launch their own ChipSats within three to five years. Our path will encourage a sustainable relationship between the cosmos and humanity while promoting respect, professionalism, and team bonding.

1.2 Aims and Objectives

The following objectives were derived from the mission statement to help outline the path to a successfully delivered project:

1. Perform a wide-scope market review of aspects and factors for ChipSats, including technologies, market needs, legal aspects, missions, alternative solutions, advantages, and limitations
2. Recognize major challenges (technical, legal, and commercial) which may hinder the ChipSat's potential to prosper, and propose recommendations to mitigate them
3. Identify and analyze a set of potential ChipSat missions considering the effort required, the time to market, and the value proposition. The potential interest from the educational, commercial and governmental sectors will be taken into consideration
4. Prepare a business case and legal recommendations for the ChipSat missions
5. Cross-reference each aspect before selecting a preferred ChipSat mission, which best aligns with ISU's needs and vision
6. Develop a conceptual design of a technical demonstration ChipSat mission for ISU, and inform on its TRLs

7. Recommend to ISU a five-year roadmap of all activities required to launch in-house ChipSats, and:
    i. Identify the mission benefits for ISU (Marketing team)
    ii. Provide a service requirement document (Technical team)
    iii. Provide ISU with a legal framework required for mission pursuit (Legal team)

The ChipSat team believes in the power of these small platforms to both encourage and transform new approaches to space missions. The team acknowledges the concern for space debris, as the strong leverage seen for the future of ChipSats exists in swarm or cluster deployments. As a committed group of professionals, we pledge to remain at the forefront, supporting the proposed legal framework designed to better define small satellites and their liability requirements. Together, the team believes ISU holds a key to opening up space to more communities, in more countries, and fostering deeper connections among people terrestrially through our common passion for space exploration. Space is big enough for everyone, and responsible stewardship rests within all of us.

1.3 Report Structure

The report structure will be outlined in the following paragraphs to inform the reader about the content that can be expected within the report. Each chapter will be described in order, beginning from Chapter 2.

Chapter 2 supplies a brief background overview of ChipSats. An extensive literature review was performed by the authors of this document before the current project phase. The work critically established a formal baseline for defining ChipSats and identified potential markets, technical shortcomings, projected applications, regulatory restrictions, and future opportunities. The core elements have been extracted from the literature review and summarized in Chapter 2 to help build the foundational knowledge necessary for readers to advance further through this documentation. The literature review document proceeded to serve as an anchor for the next phase of this project. Upon reflection of past works, the evidence compiled and captured in the literature review is believed to be one of the most comprehensive documents concerning ChipSats to date.

Chapter 3 provides a technical readiness overview of the identified subsystem components currently available on the electronics market which can be used to assemble a ChipSat. The relevant mass, size, TRL, and power ratings have been detailed for each respective component. This steered the follow-up component selection process and led to the derivation of a component shortlist. This subsequently informed the development of the technical framework for the ISU to develop and launch a ChipSat of their own as detailed in Chapter 5. Given the early stage of the technologies required for ChipSats missions, naturally, a series of outstanding technical gaps have been recognized. The bridging of these shortcomings may bring added value to future ChipSat mission designers through the reduction of overall ChipSat power requirements, multi-axis attitude control, and enhanced thermal regulation capabilities. These gaps and the relevant recommendations to address them have been stated in Chapter 7.

Reinforced by a well-informed literature review document, there was momentum going into the mission selection phase of the project. During this stage, members of the team were given the opportunity to flex creativity and proposed ideas for innovative ChipSat mission profiles. Chapter 4 walks through the motions of this process. A brainstorming session laid out all prospective ChipSat mission options that could be of interest, and bring value to space agencies and commercial entities. The subsequent decision-making steps for mission selection were determined by mapping commercial and scientific values against technical feasibility of the mission design. Ratings were mapped across each proposed mission accordingly before, ultimately, yielding three preferred mission profiles: Space Weather Forecasting, Lunar Communication Relay, and an Educational Outreach Mission for ISU. The Outreach Mission was aligned with the ISU Roadmap and has been detailed in Chapter 5. Space Weather Forecasting and the Lunar Communication Relay have been detailed further in Chapter 6.

Chapter 5 presents an opportunity for the ISU to offer additional space education plans and to strengthen its status as a global leader in space education. The achievement of a 'Sputnik-style' mission developed by ISU in support of an outreach campaign would demonstrate the noteworthy potential of small-scale satellite technology to the wider space community. The team was tasked with producing a Roadmap for ISU to develop, test, manufacture, and launch a ChipSat of their own in the next five years. Chapter 5 of this document details the relevant factors and strategies needed to meet this target while balancing the self-imposed institutional targets ISU has mandated on space education. Incorporated within the Roadmap are three core elements that help ensure the successful delivery of the mission; space education, ChipSat Payload Laboratory research and integration, and legal guidance.

Space Weather Monitoring and Lunar Communications are the two thought-provoking mission profiles proposed to industry and commercial players for future consideration. Chapter 6 outlines the commercial and scientific justifications for pursuing the aforementioned missions, and has been reinforced by a set of legal guidelines and technical aspects that underpin the deployment of ChipSats.

The discussion contained within Chapter 7 provides the SWOT analysis related to ChipSats and states the three key messages derived from the content presented within this report. Chapter 8 highlights the identified technical, legal and commercial gaps that demand future consideration. The recommendations advise ISU to leverage these gaps as project opportunities for forthcoming students partaking in ISU's range of space education programs.

To summarize, the information presented in this document intends to inspire, illuminate, and inform ISU and the broader space community on the notable potential of ChipSats. It is conceivable that there will be a renewed energy felt across the space community should ISU successfully launch one of their own in a few short years. Commercial and scientific missions traditionally demand considerably longer timelines and larger budgets. Ultimately, the development and launch of a ChipSat may help drive small-satellite industrial research forward toward more ambitious mission profiles such as missions for lunar communication and space weather monitoring. From an educational stance, ISU stands to benefit from both the proposed outreach campaign and the reinforcement of its reputation as a world-leading space education institution. Overall, these are exciting prospects to ISU, future mission orchestrators, space-enthusiasts, and future ISU students alike.

The opportunity to shape a compelling future using ChipSats is here. The time to act is now.

2. Background

This chapter briefly introduces the reader to the current technological, commercial, and legal state-of-the-art characteristics of ChipSats. Aspects such as market size, potential applications, customers, and competitors of ChipSats are discussed from the commercial perspective. Technology aspects such as the different subsystems that make a ChipSat are briefly touched on. Finally, an introduction to the legal challenges that this new technology represents is given.

The small satellite market is currently experiencing a period of rapid growth and ChipSats are expected to be an element of this (BIS Research, 2019). The market for AttoSats remains in its infancy stages and thus, still has no real market value. However, as a capability-driven technology, its growth is forecast to be almost parallel to technology miniaturization and could finally confirm itself as a disruptive innovation (Hein, Burkhardt and Eubanks, 2019). The emergence of a new market of ChipSats may be led by emerging space nations due to their low cost and rapid development times which lowers the barrier of entry to space compared to existing satellite technologies.

Most previously developed ChipSats have followed the same structural and integration approach; an assembly of COTS components mounted onto a Printed Circuit Board (PCB) board. Typically, one or several of the following can be found: photovoltaic cell(s), microcontroller(s), transceiver(s), antenna(s), and passive component(s) (Hein, Burkhardt and Eubanks, 2019). A variety of payloads can also be installed including imaging sensors, accelerometers, gyroscopes, magnetometers, and electromagnetic radiation sensors based in Complementary Metal-Oxide-Semiconductor (CMOS) technology (Analog, 2019; Cornell University, 2019; Perez, 2016).

One of the most advanced solutions available for photovoltaic cells is the Triangular Advanced Solar Cells (TASC) which has an efficiency of around 27% (Spectrolab, 2002). Although some alternative options have been proposed (coin batteries, usage of charged particles), none have been proven in flight (Cao et al., 2015; Matloff, 2005). For attitude control, embedded torque coils have been proposed although they have not yet been tested, and their current weight makes them unsuitable for ChipSats (Adams, 2019).

Passive thermal control is the only suitable option for the thermal regulation subsystem for this satellite type. Several options exist including thermal coatings, aluminized Kapton, and black paint (Gilmore, 2002). A variety of conceptual designs for propulsion have also been presented. Among them, the most relevant are ion electrospray, Electrodynamic Tethers (EDTs), and a solar sail.

The conventional approach has been to launch ChipSats as a secondary payload (Crisp et al., 2015). ChipSats are usually deployed following launch using 3U CubeSats (Manchester, Peck and Filo, 2013) or via direct deployment by astronauts onboard the International Space Station (Brown, 2017).

Few ChipSat projects have been developed or are currently in development. Former customers of such projects have been educational institutions or members of the general public who had an interest in space science. Both groups tend to leverage the low costs associated with ChipSat development and follow the Do-It-Yourself (DIY) approach.

There are a number of potential applications that could be derived from ChipSats which may attract future interest. Extremely large Synthetic Aperture Radar (SAR) apertures, for example, might be conceivable if ChipSats were deployed on a large scale (Hein, Burkhardt and Eubanks, 2019). The potentially high resolutions that could be achieved from such systems may bring tremendous value to sectors such as agriculture, forestry and urban planning (Moreira, 2013). Another potential application is distributed communications (Barnhart et al., 2007) through the implementation of a ChipSat mega-constellation that facilitates the relay of signals between any two points on Earth (Hein, Burkhardt, and Eubanks, 2019). Such communications architecture may bring value to the Industry 4.0 revolution (Rathnasabapathy, 2018) where there is focus on advancing the Internet of Things (Alcácer and Cruz-Machado, 2019) and self-driving vehicles (Lanctot, 2019). Disaster management response is another domain where ChipSats may be able to make an impact since ChipSats may be deployed much more rapidly than larger satellite platforms (Hein, Burkhardt, and Eubanks, 2019). In terms of exploration missions, Breakthrough Starshot have proposed ChipSats venture to the Alpha Centauri star system (Parkin, 2018).

There has been only one successful ChipSat mission to date; KickSat-2 led by Zachary Manchester. It launched more than 100 Sprite ChipSats aboard a 3U CubeSat in 2019 (Wall, 2019). The project was fully funded through a successful crowdfunding campaign, all except the launch which was provided by the National Aeronautics and Space Administration's (NASA) Educational Launch of Nanosatellites (ELaNa) CubeSat program. The initiative managed to raise $74,000 from 315 donors and sponsors. The first mission, KickSat-1, was unsuccessful due to a timing failure in the ChipSat deployment. A high energy particle was believed to have reset the onboard timer causing the CubeSat mothership to burn up in the atmosphere before the scheduled ChipSat release time. Fortunately, the initial funds raised, supplemented by NASA's support, made it possible to repeat the mission a second time. The project's objective was to democratize access to space by reducing cost (Manchester, 2015). The ChipSats were intended to send short messages to a network of amateur ground stations (Manchester, Peck and Filo, 2013). Six of the ChipSats onboard KickSat-2 were SpinorSats developed by students from the University of California, Berkeley. These ChipSats were intended to be partially maneuverable by using torque coils (Brashears, 2018).

Following the success of Kicksat-2, a handful of other organizations expressed intent on launching ChipSats. AmbaSat, for instance, is following a similar route to KickSat and planning to launch its first mission in 2021. Another company, Thumbsat, develops 10 gram plus PCB-based satellites and offers an all-inclusive service to customers with their payload. ThumbSat launches the customers' payloads aboard their satellites, manages the satellite bus engineering, and manages the associated bureaucratic procedures. In other words, the customer only needs to focus on their payload (ThumbSat, 2017). Unfortunately, their plans were brought to an end following two license rejections for launch by the Federal Communications Commission (FCC) (Federal Communications Commission, 2019). A STEM initiative led by Robert Twiggs (Vaspace, 2019) used ThinSats as a core element for their outreach campaign. ThinSats are 280 grams in mass and are, therefore, not ChipSats. However, their previous use in supporting an outreach campaign is relevant to this project.

From a legal standpoint, the International Space Treaties applicable for small satellites will apply to ChipSats. This includes regulation concerning registration, jurisdiction, control, and liability under the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies (Outer Space Treaty, OST) (Outer Space Treaty, 1967). Moreover, these topics are increasingly regulated under National Space Law.

During pre-launch, the expected legal issues will be in registration, licensing, and frequency allocation. It is the responsibility of the State to authorize, monitor, and regulate national space access. Additionally, the State must take on the liability of its nationals to act following its internal-facing space legislation while also satisfying its external international accountability.

Before launching a satellite, operators must take careful consideration into coordinating frequency allocation and allotment to avoid Radio Frequency Interference (RFI) and disruption from another satellite (Weeden, 2013). The International Telecommunication Union (ITU), an agency of the United Nations, ensures the appropriate use of the Radio Frequency (RF) spectrum through international coordination and frequency allocation. The ITU maintains the Master International Frequency Register (MIFR), which contains all frequencies in use and has been notified to ITU. New users must consult the MIFR before selecting a frequency and designing the payload's transmitters, antennas, and receivers. ITU divides the Earth into three regions:

1. Region One: Europe, Africa, Russia, and Mongolia
2. Region Two: North Americas, South Americas, and Greenland
3. Region Three: Asia, Australasia, and the Pacific region

These regions are further divided into over 40 frequency bands which can have exclusive allocations for broad international use, or shared allocations for regional or international use. Currently, there is no regulatory definition for small satellites in the ITU Radio Regulations (RR), and no provisions specific to small satellites. The only global primary satellite frequency available to small satellite systems is 144–146 MHz, although frequencies from 14 MHz to 10,500 MHz can be used on a secondary service basis. Small satellite projects such as ChipSat constellations must find a method to proceed within the current ITU regulatory framework (Johnson, 2014). Currently, ChipSats utilize only amateur frequencies.

Export control regulations are critical in the manufacturing and transfer of space objects, especially satellites. The objectives are to ensure national security (intrinsically linked to space from the first legislative documents), as well as peace, in alignment with the interest of the OST (Outer Space Treaty, 1967). Export control regulations apply depending on the nationality of the person exporting, the origin of the product and the nature when there is exportation. Exportation can be defined as any transfer of material, software, technology, know-how, information to a foreign recipient, or a citizen in foreign territories (Lecas, 2019). Primary international agreements include the Missile Technology Control Regime (MTCR) and The Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies (Wassenaar Arrangement Secretariat, 2017). Each country then has a specific national export control regulations framework which defines which authorization is required. The degree of strictness is dependent on the countries. One of the most used is the International Traffic in Arms Regulations (ITAR)/Export Administration Regulations (EAR) regime in the United States. In Europe, the framework for the European Union (EU) export control regime was established in the Council Regulation (EC) n°428/2009 (European Union, 2009).

During launch and operations, the States involved retain jurisdiction and control over space objects. In the event of damages caused by satellites either on Earth or in space, the launching State remains internationally liable. This covers full liability for damages on Earth and fault-based liability in space. Addressing liability for small satellites is especially important as the international legal framework surrounding liability is inclined toward State-based responsibility, and less so towards companies or universities. An added key aspect of liability, both on an international level and in national space legislation, is insurance. Indeed, according to the international legal framework outlined by the OST and the Liability Convention (LIAB), only States are liable. More governments are issuing National Space Laws to place a liability cap, and specify that companies or universities launching satellites are required to have insurance. Nevertheless, international and national legal frameworks do not specify if small satellites require insurance (Gaubert, 2014).

Finally, at the end-of-life for these satellites, space debris mitigation is required. One of the key concerns regarding ChipSats is its potential contribution to the already considerable quantity of space debris encircling the Earth. It is vital to ensure that each ChipSat mission plans to minimize the space debris footprint left at its scheduled end-of-life.

3. Technology Readiness Overview

This chapter describes the various ChipSat subsystems, proposes potential COTS components for them, and analyzes their TRL using the following classifications (see Figure 3.1).

Highly Appropriate & High TRL (TRL 7-9)	Further Analysis required (TRL 4-6)	Inappropriate & / or Low TRL (TRL 1-3)

Figure 3.1. Classification of TRL used throughout the report

TRLs are used to assess the maturity of technologies during their development, and establish a consistent and coherent baseline to compare the preparedness of new technologies to be used on real missions. Table 3.1 briefly summarizes the different TRL levels as defined by NASA.

Table 3.1. Definition of TRL levels (NASA, 2012)

TRL Level	Description
1	Basic theory observed and reported

2	Technology concept baseline established
3	Proof-of-concept of critical function and/or characteristic
4	Breadboard/component in laboratory
5	Breadboard/component functioning in a relevant environment
6	Subsystem prototype functioning in a relevant environment
7	Prototype functioning in space
8	Flight-qualified through one demonstration
9	Flight-proven through several successful missions

This analysis is performed considering a hypothetical ChipSat in Low Earth Orbit (LEO) (an altitude of 300 kilometers has been used as a reference) capable of communicating to Earth ground stations.

3.1 Payload

After an analysis of different payloads feasible for use in ChipSat missions, an average of the values of some of their characteristics was made. As a result, a hypothetical ChipSat is considered to carry a payload with the following standard technical specifications:

1. Power consumed: 30 mW
2. Mass: 2 g
3. Size: 20 mm x 20 mm x 2 mm
4. Measurement frequency: compatible with Attitude Dynamic Control System (ADCS) and communications subsystems
5. Operational working temperatures: (- 200°C) - (+ 150°C)

The values listed above can change depending on the payload and the mission that the ChipSat is expected to accomplish. It is also assumed that the ChipSat size is 5x5x0.08 cm.

3.2 On-Board Data Handling

A fundamental component of the ChipSat architecture is the microcontroller, which acts as an On-Board Data Handling (OBDH) subsystem. Such subsystems deal with the generation, handling, and storage of data onboard the spacecraft. Given the power generation constraints of ChipSats, an integrated low-power solution is essential. Moreover, since radiation tolerance may be needed for some missions, a special radiation-hardened Field-Programmable Gate Array (FPGA) may be an alternative solution (Hein et al., 2017); it is recommended to further analyze such alternatives.

Regarding the main specification of the OBDH subsystem, two commercial solutions with a TRL of 9 are proposed in Table 3.2 below. These microcontrollers have been chosen based on their power consumption, size, and performance.

Table 3.2. Data Handling Subsystem specification

Component	Size (mm)	TRL
MSP430 (16-bit)	Different packages options, from 3.10 x 3.10 with BGA package (Texas Instruments, 2012)	9
ATmega328P (8-bit)	7.0 x 7.0 x 1.0 (Atmel, 2015)	9
CC430 (CC1101 + MSP430)	7.0 x 7.0 x 1.0 (Texas Instruments, 2018)	9

The TRL level of these microcontrollers have been taken into account. The suggested components, in fact, have either been tested directly in ChipSat missions or in other relevant small satellite deployments (Ambasat, 2020; Manchester, Peck and Filo, 2013).

3.3 Power Generation

Power generation using solar cells can be challenging since attitude control is not yet available for such small systems. If photovoltaic cells are used, they may not face the Sun and may not be able to support the entire satellite due to this lack of energy generation. It is important, then, to study the ChipSat directional efficiency, which is the fraction of the energy perpendicular to the ChipSat surface. Depending on the mission architecture selected, two main scenarios can be considered:

Architecture 1 - Fixed Orientation

The deployment system gives the satellite an initial angular velocity which will allow the ChipSat to maintain a fixed orientation in space through gyroscopic stabilization. This will allow the satellite to maintain a Sun-oriented attitude during the illuminated parts of the orbit. The proposed solution is feasible for short missions in which the relative position of the Sun and the Earth does not change substantially. It should be noted after six months, the cells will get incrementally less sunlight while the Earth moves around the Sun. When they are facing the opposite direction, they receive no sunlight at all. If this mission architecture is selected, a directional efficiency between 0.7 - 0.9 is predicted.

Architecture 2 - Random Orientation

The deployment system gives the ChipSat a random attitude motion, i.e. the ChipSat is tumbling. This changes the photovoltaic cells directional efficiency as a function of time. In Figure 3.2, a set of ChipSats with different angular velocity orientations are shown, together with the maximum, minimum, and average values for the directional efficiency.

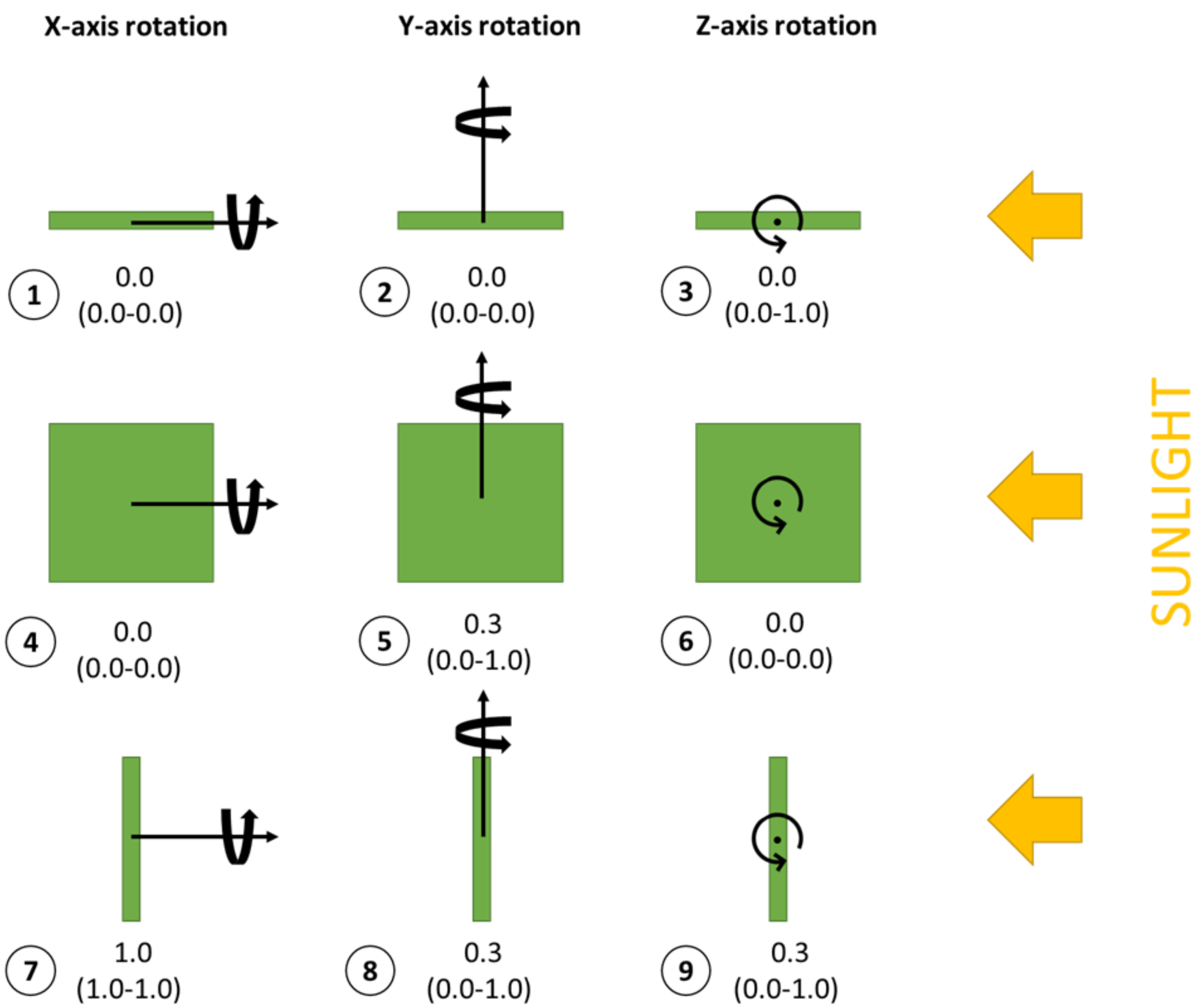

Figure 3.2. Directional efficiency for various ChipSat orientations.

For cases 3, 5, 8 and 9 the directional efficiency varies from 0.0 - 1.0, however the average value for an entire rotation is:

$$e_{directional} = \frac{1}{2\pi}\int_{-\pi/2}^{\pi/2} \cos\theta \, d\theta = 0.3 \quad \text{.......................................Eq. (3.1)}$$

For a generic ChipSat with a random orientation, the following applies:

$$e_{directional} = \frac{1}{2\pi}\frac{1}{\pi}\int_{-\pi/2}^{\pi/2}\int_{0}^{\pi/2} \cos\theta \cos\lambda \, d\theta \, d\lambda = 0.1 \quad \text{...Eq. (3.2)}$$

For further calculations, the directional efficiency for this architecture will be considered to be 0.1.
For small satellites, some commercial solutions for photovoltaic cells are proposed. Most of the providers sell custom-sized solar cells, which is ideal for ChipSats. Such photovoltaic cells are proposed in Table 3.3 below.

Table 3.3. Solar Cell Specification (NASA, 2018)

Solar Cell	Efficiency (%)	Mass per unit area (mg/cm^2)	TRL
Spectrolab TASC	27	105	9
SpectroLab UTJ	28.3	84	9
SpectroLab XTJ	29.5	84	9
AzurSpace 3G30A	29.6	118	9
Azur Space 3G30C Advanced	29.6	118	8
CESI Solar cells CTJ30	29.5	89	9
SolAero XTJ & Prime	29.5 - 30.7	84	9
SolAero ZTJ	29.5	84	9
SolAero ITJ	26.8	84	Unknown
SolAero UTJ	28.3	84	Unknown
SolAero XTJ	29.5	84	Unknown
SolAero XTJ Prime	30.7	84	6

An average efficiency of 29.5% (range: 28.3% - 30.7%), and a mass per unit area between 84-118 mg/cm^2 can be observed as general trends. The value of the power generated by the ChipSat can vary upon the function of the mission architecture selected.

The power generated in LEO is calculated by the following equation:

Power generated = 1,368 W/m^2 · (solar cell efficiency) · (directional efficiency)……………………Eq. (3.3)

(Wertz, Everett and Puschell, 2011)

Table 3.4. Data for power generation, architecture 1 and 2

Architecture	Solar cell efficiency	Directional efficiency	Power generated (mW/cm^2)
Architecture 1 *Gyroscopic motion*	0.29 ± 0.01	0.8 ± 0.1	32 ± 4
Architecture 2 *Random orientation*	0.29 ± 0.01	0.1	4 ± 1

Applying the equation mentioned above with the data of Table 3.4, the following has been obtained.

Architecture 1

Power generated = 1,368 W/m² · (0.29 ± 0.01) · (0.8 ± 0.1)

Architecture 2

Power generated = 1,368 W/m² · (0.29 ± 0.01) · 0.1

The final results of the above equation for the average power generated for each architecture are as follows:

Architecture 1: 32 ± 4 mW / cm²
Architecture 2: 4 ± 1 mW / cm²

As can be seen, if attitude of the ChipSat can be controlled, the power generated is 8 times higher than if no control can be achieved. For most of the LEO missions, Architecture 2 can be used. Redundancy will allow some of the ChipSats to work properly while others will be lost.

3.4 Power Storage and Regulation

Power storage is needed to communicate and take periodic measurements in a controlled manner. If no power storage system is used, ChipSat operation is limited to utility only when the satellite solar cells are pointing to the Sun. However, power storage is still one of the main gaps in ChipSat development. Because of weight constraints, the commercial solutions are limited to coin batteries (Perez and Subbarao, 2016). However, due to the power capacity limitation and the lack of space-related applications conducted with this type of battery, the TRL of such a solution is very low (TRL 3). Following an analysis of alternative battery types, it has been concluded that no options are prepared for this type of mission with ChipSats due to thermal and mass constraints. Furthermore, since all the selected components have operational voltages ranging between 1.8 and 3.3V, and the photovoltaic cells deliver 2.2V, no voltage regulator is needed (Spectrolab, 2002).

3.5 Attitude Determination and Control Subsystem

The components used to predict the ChipSat attitude are highly variable, and depend mainly on the requirements of the mission. One of the main characteristics that has to be taken into consideration when selecting the component is the desired accuracy: its mass, size and power consumption will highly depend on the needed parameters. Inertial Measurement Units (IMUs), magnetometers and combinations of those have been considered. More precisely, the following different components are proposed: a digital compass (magnetometer + accelerometer), or a magnetometer, or a 6-axis and 9-axis IMU.

As a general rule, a trade-off between power consumption and accuracy must be taken into consideration, taking into account that mass and size of the component will also vary. For ChipSat applications, a compass sensor may not always be the best solution since a precise determination of the magnetic field is needed (magnitude and direction) to calculate a reliable attitude position. This is why it is recommended to use a magnetometer instead. Regarding the inertial modules, two options may be used: 9-axis or 6-axis IMU (a

9-axis IMU is recommended if no other magnetometer is installed). For attitude determination, the team provides the following recommendations:

1. Use at least one magnetic-field based sensor and an inertial unit for attitude determination
2. Fuse both sets of data with a Kalman filter
3. The following architecture is recommended: Use a high-performance position determination sensor on board of the deployment unit (e.g. Sun or star tracker). Just before releasing the ChipSats, inform the ChipSat of the current position. After that, integrate the position using, at minimum, a reliable 6-axis IMU (including a magnetometer is also recommended)

For the selection of components, the following commercial solutions are shown in Table 3.5 below.

Table 3.5. ADCS component specification

Component	Part number	Mass (g)	Size (mm)	TRL	Power	References
Compass	HMC5883L	0.018	3.0x3.0x0.9	6	0.3 mW	(Honeywell, 2013)
Magnetometer	HMC1053	TBD	3.0x3.0x0.9	7	30 mW	(Honeywell, 2006)
	MAG3110	TBD	2.0 x 2.0 x 0.85	6	1.8 mW	(NXP, 2013)
	BMM150	TBD	1.6x1.6x0.6	6	1.6 mW	(Bosch, 2020)
9-axis IMU	ICM-20948	TBD	3.0x3.0x1.0	7	2.5 mW	(Invensense, 2016)
	LPMS-ME1	0.3	12x12x2.6	6	60 mW	(LP-research, 2020)
6-axis IMU	LSM9DS1	TBD	3.5x3.3x1.0	8	2.0 mW	(STMicroelectronics, 2015)
	VN-100	TBD	36 x 33 x 9	6	220 mW	(VectorNav, 2017)
Magnetotorquer	ZARM MT0.1-1	<3	⌀3.5 x <55	7	295 mW	(Holger, 2014)

Orientation control is important as it will allow the ChipSat to position itself at an optimal orientation for each stage of the mission. Examples of that include antenna orientation, photovoltaic cell directional selection, and attitude control to monitor or control the drag force (for LEO).

For ChipSats, the team has determined that torque coils, which make use of the magnetic field, may be a good fit for active attitude control technologies. A benefit of torque coils is that they are very small and light, and consume a low amount of energy. However, because the exerted forces depend on the magnetic fields, this type of technology is limited to LEO and highly accurate mapping of the orbited body's magnetic field is needed. Therefore, this field mapping will be a unique precursor to each ChipSat mission. It is concluded that torque coils are not applicable for lunar missions, nor for longer distance missions such as the ones for interstellar exploration. However, considering current technology, the magnetorquer proposed weighs less than 3 grams. For two-axis attitude control, two magnetorquers must be added. This modification will consume 60% of the total mass budget, which may be excessive for certain missions. For three-axis attitude control, three magnetorquers must be added (90% of the total mass budget).

3.6 Propulsion

Propulsion systems for ChipSats are in a preliminary development phase and have not yet been tested . Because of the 10 gram weight constraint, this type of satellite cannot accommodate any conventional propulsion system. Three substitutes for propulsion systems are presented:

Electrodynamic Tether

This system deploys conducting wires from the ChipSat to interact with the Earth's magnetic field, which makes it efficient for low-mass satellites. While the concept has been developed, the system remains to be tested. An EDT of 3 - 10 meters in length could provide sufficient thrust for a 1 - 100 gram satellite to overcome drag in LEO orbit. It needs a paired mass at the end of the tether; another ChipSat as the paired mass. The pairing over an EDT provides electrical contact with plasma and in-flight stability (Bell et al., 2013). Single tether for thrust may be insufficient for overcoming the gravity gradient force across such satellites; an array of short tethers with different axes of orientation might solve the problem (Burkhardt, 2019).

Solar Sail

This concept utilizes the momentum of photons to propel a spacecraft. The attitude and orbit of a ChipSat can be managed through the adjustment of the sail angle. However, it is limited to the inner solar system as the acceleration of the solar sail is inversely proportional to the distance of the spacecraft from the Sun. The concept has been developed and tested in other types of small satellites, however the system has not been tested for ChipSats (Burkhardt, 2019).

Laser Sail

Laser sails use Earth-based, and potentially space-based lasers to propel spacecraft using the momentum transfer principle. Focused energy can produce a higher thrust than solar sails but needs high precision lasers. Attitude control can be achieved by targeting the laser at different points on the sail. A new concept of Alpha sail for Sprite is currently under development at Cornell University, which will be launched as a part of NASA's ELaNa program. This concept incorporates a laser-propelled sail with four Sprites, one at each end, in the initial configuration of a CubeSat (Cornell University, 2019). No prototypes have been tested but the concept is being developed.

To conclude, developing a dedicated propulsion system on a ChipSat is very challenging. The above mentioned propellantless propulsion techniques can be potential candidates depending on the mission requirements, but the TRL of such systems is very low for ChipSats and hence can prove to be a topic of interest for future researchers.

3.7 Printed Circuit Board

The most appropriate solution for ChipSat applications is a rigid FR4 PCB coated with Kapton tape, thanks to its thermal, dielectric and physical characteristics. The glass-reinforced epoxy laminate PCB substrate can provide adequate rigid support, while the Kapton coating can provide radiation and thermal protection. Typically, satellites require harnesses for electrical connection, although ChipSats carry electrical signals through the layers of copper in the PCB. Table 3.6 below shows the characteristics of several structure options considered for ChipSats.

Table 3.6. PCB Features Specification.

Component	Density (g/cm^3)	TRL	Temp. range
PCB (FR4)	1.8 (EDCOR, 1997)	9	−50°C to +110°C (Nanotech-elektronik, 2020)
Kapton Tape	1.42 (GoodFellow, 2008)	9	−269°C to +400°C (Grovesales, 2020)

Future solutions may utilize carbon fibre reinforced polymer (CFRP) as a material for PCBs (Vasoya, 2006). In addition, multi-chip modules could be considered for similar applications (Enlow, 1998).

3.8 Thermal Control

Given the majority of ChipSat components operate across a range smaller than the anticipated temperatures in LEO (i.e. between -170ºC and 123ºC), appropriate thermal protection is required (Israel, 2015). Moreover, for applications where data has to be taken during re-entry (e.g. taking data of the upper layers of the atmosphere or calculations the ballistic coefficient), a very low absorptivity is recommended. Generally, the following have to be taken into account during thermal control subsystem selection:

1. No active thermal control is possible with the current technology because of size, weight and power constraints. However, Joule heating, which is heating due to the passage of electrical current through an electrical conductor, may be considered as a means to counteract eclipse temperatures
2. It is recommended to use options such as using black paint or distributing the components considering their heating rate. Different materials can be used in the antennas to accomplish the requirement of the communication and operational temperature range, but they should be transparent to RF energy

3. Some examples of surface finishes or coating used before on satellites are shown in Table 3.7. These materials have been previously proven in space with successful performance (Wertz, Everett and Puschell, 2011), which gives them a TRL of 9. On the other hand, these technologies have not been used in ChipSats, which is considered a TRL of 3

Table 3.7. Thermal Control Specifications (Wertz, Everett and Puschell, 2011)

Passive thermal component	TRL
White paints: S13G/LO, Z93, YB71	9
Black paints: D1111, Z301, 3M Blac Velvet, Chemglaze Z306	9
Metallic treatments: e.g. anodizing	9
Kapton film (coating to FR4 PCB)	9

3.9 Communications

The communication subsystem is a crucial component of the ChipSat to achieve a successful mission. To communicate back to Earth, two main elements are required: the transceiver radio module and the antenna (Wertz, Everett and Puschell, 2011). It is a challenge to close the communication link between a ChipSat and the ground station due to the limited output power of the transmitter, which is in the vicinity of 10 mW. Other elements that contribute to the complexity of the communication problem are the lack of attitude control and the limited RF bandwidth (Manchester, 2015). The former results in the use of a low-gain antenna with an omnidirectional gain pattern. Furthermore, the antenna should be flexible and easy to deform, while still returning to the original shape, such as nickel-titanium (Manchester, 2013).

Current technology can implement a communication link from the ChipSat to Earth, with examples shown in Table 3.8 below for different transceivers. The result of the commercial trend to these small-sized radio modules and antennas is that these COTS components can provide ultra-long range spread spectrum communication, while having a high interference immunity and minimizing the current consumption.

Table 3.8. Communication Specifications

Component	Part number	Mass (g)	Size (mm)	TRL	Power Consumption	References
Transceiver	CC1101 Sub 1-GHz	0.07	4 x 4	7	16 mW	(Texas Instruments, 2020)

	CC430 (CC1101 + MSP430)	0.14	7.0 x 7.0	9	40 mW	(Texas Instruments, 2018)
	Anaren Integrated Radio	0.4	9 x 12 x 2.5	>5	58 mW	(Anaren, 2011)
	LPRS eRIC9 Radio Transceiver	1.5	15 x 20 x 2.2	>5	115 mW	(Low Power Radio Solutions Ltd, 2015)
	RFM95 Ultra-long Range Transceiver Module	2.0	65 x 120 x1.8	8	396 mW	(Hope Microelectronics, 2006)
Component	**Part Number**	**Mass (g)**	**Size (mm)**	**TRL**	**Power Rating**	**References**
Antenna	ANT-LTE-SP610	1.5	40 x 10 x 2.8	>6	10,000 mW	(Linx Technologies, 2019)
	TAOGLAS Cyclone	2.4	130 x 30 x 0.2	>6	50,000 mW	(Taoglas, 2019)
	Molex 212570-0200	1.05	40 x 15 x 2	>6	2,000 mW	(Molex, 2020)

A communication budget study has been performed in order to estimate the necessary specifications of the radio transceiver. It has been concluded that among the analyzed components, only the CC1101 can be used for a ChipSat. Considering the CC1101 Sub 1 GHz transceiver, the frequency bands are 300-348 MHz, 387-464 MHz, and 779-928 MHz. For this component, a communication budget has been performed (Wertz, Everett and Puschell, 2011). The results obtained are shown in Table 3.9 below.

Table 3.9. Communication Budget

Center Frequency and Bandwidth	425.5 MHz, 387-464 MHz
Altitude	300 km, but slant is any given by elevations higher than 5 degrees
Data Rate Required	600 kbps
Free Space Loss	148.5
Other Losses	2.06 dB
Tx Power	16mW
Tx Effective Isotropic Radiated Power (EIRP)	-16.9

Rx Efficiency	0.65
Rx Diameter	1m
Rx Gain	17.2
Rx Received Power	-155.8 dB
C/N	-30.8dB
Eb/No	-9.8 dB
Eb/No + 640 chips PRN* Gain	18.3 dB

*Matched filtering using Pseudo-Random Noise (PRN) code as an optimal linear filter technique to maximize the Signal-to-Noise Ratio (SNR) (Manchester, 2013).

3.10 Mass, Size, and Power Budgets

To study the mass, size and power budgets, the average values for each subsystem have been considered, and only the components under the classification “highly appropriate and high TRL” have been taken into account (i.e.: green). Time-to-market has also been considered. Then, a PCB-board ChipSat has been assumed. The following has been obtained in Table 3.10 below:

Table 3.10. Subsystem Component Specifications

Subsystem	Component	Mass (g)	Size (mm)	Power (mW)
OBDH	Microcontroller	<1.0	(6 - 10) x (6 - 10)	10 - 20
ACDS	Magnetometer	<1.0	(2 - 3) x (2 - 3)	30
	9-Axis IMU	<0.3	(3 - 12) x (3 - 12)	3 - 60
Structure	Kapton-Coated PCB	0.2 - 1.6	(35 - 100) x (35 - 100)	0
	Solid PCB	0.7 - 6.0		0
Payload	TBD	<2	(<20) x (<20)	<30
Communications	Transceiver	<1	4 x 4	10
	Omnidirectional Antenna	1.0 - 1.5	100 mm (x2)	

Power Generation	Photovoltaic Cell	84 mg/cm²	Depends on the architecture.	A1: (32 ± 4) mW / cm² A2: 3 ± 1 mW / cm²
Others*		<1		10

(*) Others: refers to any electronic components such as resistors, capacitors, etc. or any other component such as protective paints.

As it can be seen in the table above, the component that weighs the most and limits the size of a PCB-based ChipSat is the structural subsystem. If the ChipSat is assumed to measure 10 centimeters x 10 centimeters, the PCB will weigh 6 grams, which limits the weight allocated to photovoltaic cells. The objective of the table is to present some trends about mass, size, and power without aiming to design a ChipSat, as the final budget will entirely depend on the type of mission.

3.11 Gaps and Recommendations

The team proposes the following recommendations as a result of the ChipSat technology readiness analysis:

1. Thermal control is one of the main limitations of ChipSat missions today. Currently, only passive thermal control can be considered and, as a result, limited control can be achieved
2. The above-mentioned limitation has a direct influence on the power storage. Batteries are not capable of operating in ChipSat missions. This limits both the power available for the payload subsystem, and the parts of the orbit where the ChipSat can operate (no energy is available during eclipse)
3. Maneuverability and attitude control is another critical limitation for ChipSats with current technology. Although magnetorquers can be a viable solution for ChipSat attitude control during missions involving a well-defined electric field around the orbited celestial body, their mass is currently a limitation for most missions. The team recommends conducting further research on these, since attitude control is a critical requirement for many missions
4. Consider other types of systems or materials for the structural subsystem. The team recommends to further study thinner PCB boards and multichip modules covered with kapton.
5. Further research must be done regarding the communications subsystem. The limited power available limits the subsystem capacity
6. Identifying and logging the location of the ChipSat when it makes its sampling.

4. ChipSat New Opportunities

The main advantage of ChipSats is their low mass and associated low cost. This enables hundreds of ChipSats to be launched into orbit or towards other bodies in the solar system to acquire in-situ measurements. However, it is important to consider that ChipSat payloads are also limited by their low mass, and applications around Earth are restricted due to space debris concerns.

The objective of the ChipSat team project was to brainstorm potential missions enabled by ChipSat technology. The mission ideas and the process of creating, analyzing and selecting them will be discussed in the following sections.

4.1 Mission Brainstorm

A series of brainstorming workshops were conducted with the entire team to establish a list of potential missions enabled by ChipSat technology. A selection of the new opportunities proposed during the workshops are described below with their associated ratings for commercial value, scientific value and engineering feasibility. The ratings given are between 1 and 10, where 1 is the lowest and 10 is the highest rating.

The values were assigned based on the expert judgement of marketing and engineering specialists within the team. As there was not sufficient time to investigate all of the missions in detail, these values helped with choosing the four missions with the highest potential to perform further research on, before deciding on the final two missions that are presented in this report as case studies. The selection process will be explained further in Section 4.2.

1. Earth Atmospheric Studies

ChipSats can theoretically orbit at lower altitudes than traditional satellites if they are designed within certain criteria. This may enable investigation of the “ignorosphere”, the area above the altitude stratospheric balloons can reach but below other satellites.

Commercial Value

Low (3). As the altitude is above where aircraft fly and below where satellites orbit, there are unlikely to be many commercial customers for this zone.

Scientific Value

Medium (6). The ignorosphere, otherwise known as the mesosphere, is relatively poorly studied when compared to data available on the stratosphere. Strong winds, gravity waves and planetary waves may be further studied for scientific value.

Engineering Feasibility

High (8). The ChipSats incorporate the characteristics necessary for such a mission: low mass, swarm capability, and have typically a low lifetime.

2. Space Weather Forecasting

Space weather, including solar particle events, can affect both space and Earth operations. ChipSats may be able to assist with a prediction of space weather events by providing magnetic field data to calibrate space weather forecasting models.

Commercial Value

High (10). Space weather events can negatively affect both ground and space-based technology, as well as human health. A large space weather event would result in a significant economic cost due to society's dependence on technology today.

Scientific Value

High (10). Additional data related to the Earth's magnetic field will help us better understand space weather and how it affects our planet and our solar system.

Engineering Feasibility

High (7). As long as the ChipSats are operational in Earth's environment, a ChipSat would be capable of obtaining distributed information of space weather. Sensors to get information about the magnetic field seem feasible in the near future.

3. Satellite Health Monitoring

Launching a swarm of ChipSats to monitor the health of a satellite such as the Hubble Telescope can be favorable. As ChipSats have their own power supply and communications system, they can act as independent external visual sensors to give further data to onboard sensors that measure key satellite health parameters.

Commercial Value

Medium (6). Companies who invest in expensive infrastructure will want to monitor its health over time. Having a visual explanation of why something such as a heat shield failed will aid in contingency planning for future mission planning.

Scientific Value

Medium (6). Protecting equipment for missions from a scientific viewpoint is beneficial for the same reasons as stated in Market Need, however using ChipSats as supporting visual sensors will be dependent on mission budget.

Engineering Feasibility

Low (3). Due to the lack of maneuverability of ChipSats, this mission concept seems unfeasible. The rendezvous proximity guidance would be too complex to be performed by a ChipSat.

4. Space Debris Tracking

ChipSats could be attached to undetectable space debris objects in orbit so their location can be tracked at all times. This would require a spacecraft that can find and rendezvous with pieces of space debris in order to attach a ChipSat to it.

Commercial Value

Low (3). Most major pieces of space debris are already being tracked, and pieces of space debris that are small will be difficult to find even though a one cubic centimeter piece can be devastating.

Scientific Value

High (7). Being able to track space debris effectively will help mitigate against Kessler syndrome, such as collisions between space debris objects that may continue colliding.

Engineering Feasibility

Low (2). The technology to attach ChipSats to space debris objects is non-existent. A tethering system would increase the mass above the allowable mass limits for ChipSats.

5. Outreach Mission

ChipSats have limited payload capacity but can easily be used for outreach and communication with the ground. A ChipSat could deliver messages to Earth, such as “Space is for Everyone” from orbit to encourage community involvement with space.

Commercial Value

Low (2). Using ChipSats for outreach is useful to encourage young people to study STEM and space-required subjects to help build the space industry, however this is normally a non-profit venture.

Scientific Value

Low (3). The scientific value of an outreach mission is very limited as it is unlikely to include scientific payloads on board. However, as ChipSats are a new technology an outreach mission can act as further demonstration of the feasibility of ChipSat missions.

Engineering Feasibility

High (9). The easiest mission possible with a ChipSat: LEO and simple mission objective which results in a high feasibility score.

6. Biological Experiments

ChipSats could be an effective method of launching biological samples into the space environment for scientific research. Small samples would be exposed to radiation and microgravity, and basic measurements could be taken.

Commercial Value

Medium (4). This approach to experiments might lower the entry barrier for institutes and universities to conduct biological studies.

Scientific Value

Medium (6). Lowering the entry price for space-based experiments would allow less demanded research to be conducted which could provide unique insights. An increase in the number of research experiments performed will follow.

Engineering Feasibility

Medium (6). The ChipSat’s orbit would be near Earth, which makes the mission feasible. However, having reasonable-sized samples would complicate the integration of the ChipSat’s components.

7. Lunar Communication Relay

ChipSats can serve as a communications relay for lunar rover missions when line of sight with an orbiting satellite isn't available. In addition, the ChipSats can measure properties of the lunar environment as they descend towards the surface upon deorbiting.

Commercial Value

High (8). Creating an easily deployable swarm of communication satellites can temporarily boost the lunar exploration missions, which aligns with many space agencies' strategies. Further commercial missions can utilize the support of this constellation concept.

Scientific Value

High (7). ChipSat format is capable of providing unique scientific data to researchers and scientists on Earth. This is a unique tool to precisely measure lunar magnetosphere and provide insights into

Engineering Feasibility

Medium (6). Assuming the ChipSats are delivered in the lunar environment, the lower gravitational accelerations would extend the mission lifetime. Yet the operation of ChipSats in the lunar environment is uncertain, particularly regarding communications.

8. Mars Atmospheric Studies

The Martian atmosphere is not as well characterized as Earth's. ChipSats could be deployed from larger satellites orbiting Mars to measure properties of the Martian atmosphere from multiple locations at the same time.

Commercial Value

Medium (6). Since Mars is a point of major strategic interest of many space agencies, the future missions will not take long to be launched. ChipSat may be able to investigate the planet for a lower cost than some alternatives.

Scientific Value

High (7). Creating a 3-dimensional model of the Martian atmosphere would allow to precisely map the gas distribution, radiation level and particle density. This will give insights into the Martian history and help to evaluate further points of interest.

Engineering Feasibility: Medium (6). The challenge here would be to collect data simultaneously in a synchronous fashion. The mission concept itself is feasible, where ChipSats would descend into the Martian atmosphere, similar to the proposed Earth-applied missions.

9. Asteroid Fly-By

ChipSats could be used to investigate the properties of asteroids within the asteroid belt. They could be dropped off by a separate spacecraft as it travels through the Asteroid Belt on the way to its destination.

Commercial Value

High (8). Asteroid mining is a potential space resource utilization idea, but it requires preliminary studies. ChipSats can provide cheap, compact and lightweight means to study this area. They can be mounted as a secondary payload on a spacecraft, which would not require significant financial investments.

Scientific Value

Medium (6). ChipSats would provide preliminary reconnaissance of asteroids in the asteroid belt. Initial measurements would help to evaluate the most potential asteroids for further studies.

Engineering Feasibility

Low (2). The low feasibility relates to two aspects: the lifetime of a ChipSat and the attitude maneuverability of them. The ChipSat would have to survive the transfer time and should be able to power up at arrival. Also, the accuracy of the ChipSat's orbit is a big challenge.

10. Pictures from Outside the Solar System

Due to their low mass, ChipSats can be attached to a light sail to travel to the edge of the solar system within a decade. This could be an opportunity to take pictures looking back towards Earth, similar to the Voyager probes.

Commercial Value

Low (3). Market application of images from the outer Solar System is doubtable.

Scientific Value

Low (4). Going outside of a planet's orbital planes would provide unique measurement opportunities, 1

Engineering Feasibility

Low (3). Although it seems very futuristic, a ChipSat would be able to take a picture from the area outside the Solar System. The challenges here are not necessarily the maneuverability, but the power output and the survival of them on their way to the edge of the Solar System.

The feasibility of these mission options are reflected in Table 4.1 below.

Table 4.1. Feasibility scoring of missions

Mission	1	2	3	4	5	6	7	8	9	10
Commercial	3	10	6	3	2	4	8	6	8	3
Science	6	10	6	7	3	7	7	7	6	4
Feasibility	8	7	3	2	9	6	6	6	2	3
Total	17	27	15	12	14	17	21	19	16	10

4.2 Mission Selection Process

Each of the missions proposed during the brainstorming process was assigned a rating for commercial value, scientific value and engineering feasibility. The values were assigned based on expert judgement and plotted in Figure 4.1 below to help visualize the missions with the highest potential.

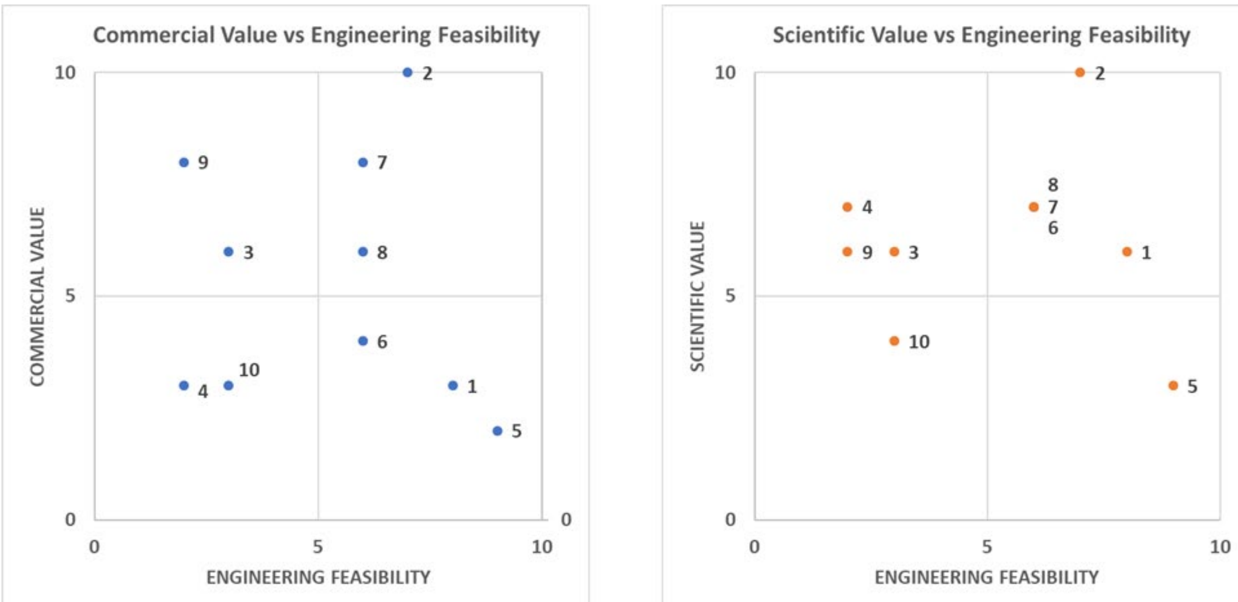

Figure 4.1. Mission Ideas Scoring Matrix.

Based on Figure 4.1, four missions with high potential, particularly in terms of commercial value, were shortlisted. The four missions selected on the shortlist were as follows:

1. Atmospheric Studies - most feasible mission
2. Space Weather Forecasting - highest overall score
7. Lunar Communication Relay - second highest overall score
9. Asteroid Fly-by - high commercial potential

In addition, the mission with the highest engineering feasibility was deemed to be the most appropriate for the ISU and will be featured in the proposed ISU Roadmap in Chapter 5.

5. Outreach Mission - highest engineering feasibility

Further research was conducted into the four shortlisted missions to ensure the team had a more accurate understanding of the commercial value, scientific value and engineering feasibility of the missions before deciding on the final two missions to be featured in this report in more detail. This decision was based on a combination of the ratings assigned and other soft criteria. The two missions that were selected to be presented as case studies of potential ChipSat missions in Chapter 6 are:

1. Mission 1: Lunar Mission
2. Mission 2: Space Weather Forecasting

These two missions ranked highly in both commercial and scientific value, as well as engineering feasibility. Both are considered to be high potential missions. Other soft criteria were also considered but not featured explicitly in the scoring matrix, such as the following:

1. Desire to select two missions with different destinations (i.e. Earth and the Moon)
2. Desire to select two missions within different application areas (i.e. science and communication)
3. Relevant expertise within the team
4. Missions must be feasible within 5-10 years

5. ISU ChipSat Roadmap

5.1 Introduction

The mission of the ISU states that: “The International Space University develops the future leaders of the world space community by providing interdisciplinary educational programs to students and the space profession” (International Space University, 2020).

The ISU ChipSat Roadmap is a proposal for the ISU to launch its own ChipSat within a five-year timeframe. It encompasses activities to develop ChipSat technology and deliver high-quality space education, while also considering the regulatory framework and opportunities for outreach.

The ChipSat Team is addressing the five strategic Institutional Objectives detailed in Chapter 5.2. to bring a range of educational and scientific benefits to the ISU (International Space University, 2019). Implementing these steps will strengthen the ISU's position as a leader in space education and will result in setting the foundation for a continuous future Research and Development (R&D) framework.

The Roadmap is composed of three key elements illustrated in Figure 5.1:

1. Enhance the ISU’s technical capability and education programs through the ISU ChipSat Program. Identify steps to develop capability in high quality space technology education, which will result in the launch of the ISU’s own ChipSat. The proposed mission is both scientific and educational. Moreover, it identifies the areas to strengthen bonds of cooperation with other universities and educational institutions.
    i. Develop the ISU’s own ChipSat hardware and software
    ii. Establish the ISU facilities for ChipSat assembly, integration and testing (AIT)
    iii. Improve curriculum of the ISU educational programs

2. Ensure compliance with the Regulatory Framework.
Proposed is guidance on the legal requirements, jurisdiction, control, liability and end-of-life regulations to outline the legal boundary conditions for the operation of an ISU ChipSat mission
    i. Guidance on authorization and registration
    ii. Guidance on frequency allocation

iii. Space debris mitigation

3. Reinforce ISU brand as a leader in Space Education by Outreach Activities.

The activities are oriented toward enhancing ISU's visibility as experts in ChipSat technology and promoting ISU's brand through external activities such as outreach and symposiums.

i. ISU ChipSat outreach campaign

ii. AmbaSat trial launch

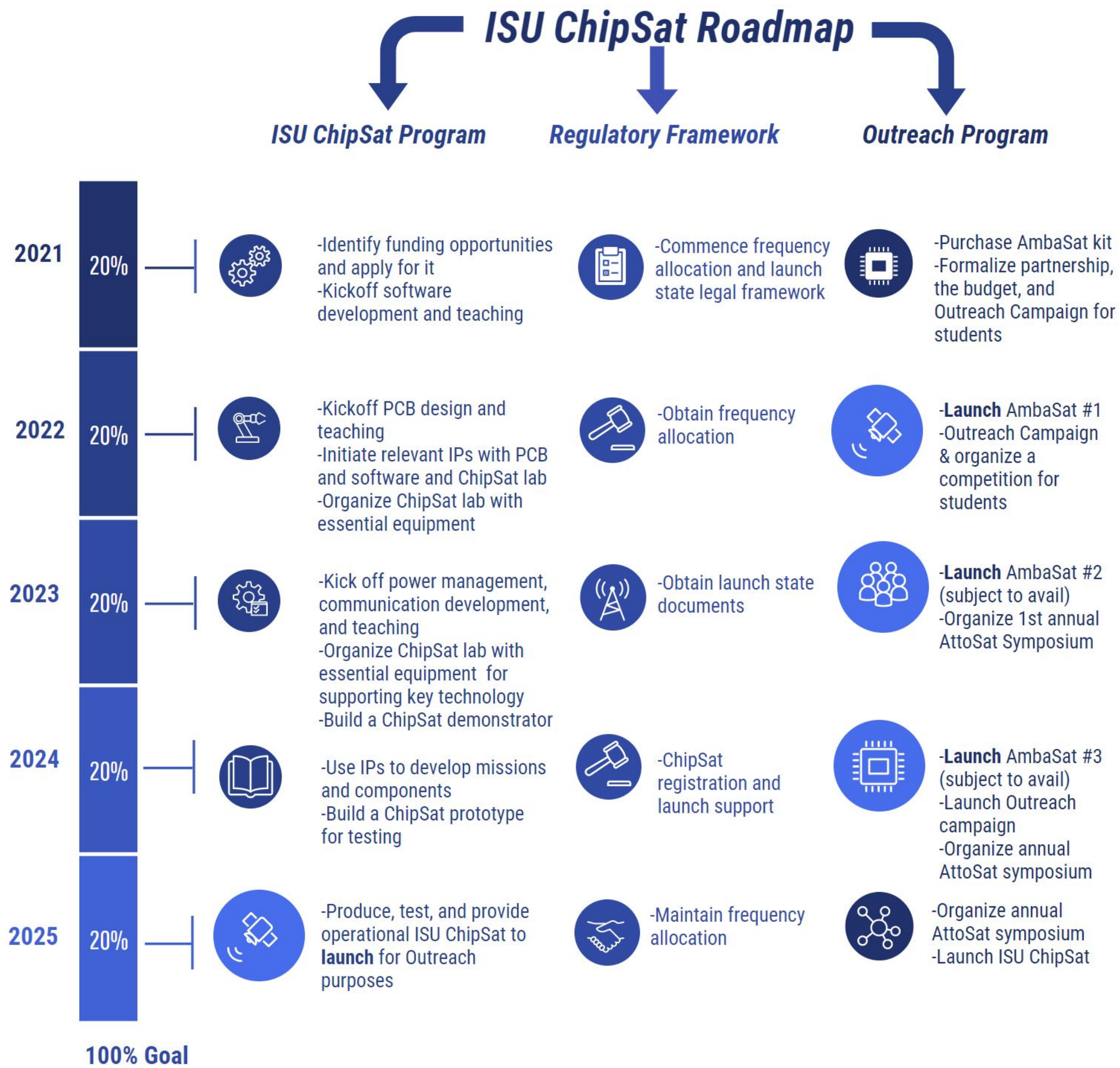

Figure 5.1. ISU ChipSat Roadmap summary

5.2 Addressing ISU Institutional Objectives

Each of the three elements in the Roadmap addresses one or more of ISU's Institutional Objectives as detailed in Table 5.1 below.

Table 5.1. ISU Institutional Objectives and the relevant Roadmap activities (ISU, 2019)

ISU Institutional Objective	Roadmap Element	Proposal
Objective One: Enhance the quality, recognition and range of programs and research (Responsible: Dean's Office)	ISU ChipSat Program	Establish a long-term ISU ChipSat Program and laboratory facilities at ISU to offer Thesis and Individual Projects related to satellite engineering as well as legal, policy and regulations Utilize the ISU ChipSat Program to enhance curriculum of the ISU educational programs (e.g. Masters of Space Studies program, MSS)
Objective Two: Increase ISU enrollment while enhancing the quality and diversity of the student and participant body	Outreach Program	-Utilize the outreach campaign to promote space education for future students (focused on increase in female admissions) and students from the geographically under-represented areas (Africa, Japan, Latin America, Middle East, Russia) Campaign will involve media coverage and highlight the educational value of satellites
Objective Three: Reinforce financial stability and ensure growth for the University	ISU ChipSat Program	Utilize ISU ChipSat Program to apply for research grants and funding for ISU laboratory and facilities
Objective Four: Promote ISU as the best source of interdisciplinary, international, intercultural space education	Outreach Program	Utilize the outreach campaign to reinforce ISU's status as a leader in space education Utilize the ability to launch ISU's own ChipSats to promote capabilities of ISU's education programs
	ISU ChipSat Program	Advertise the ISU ChipSat Program to promote the success of ISU space missions and facilities to attract students and sponsors
Objective Five: Take full advantage of key assets including ISU staff, alumni, faculty, partner organizations and of the ISU Central Campus facilities in Strasbourg	Outreach Program	Involve staff and alumni to create training materials for students Strengthen the bond of cooperation between ISU and the sponsors Attract new sponsors to support ISU small satellite applications

	ISU ChipSat Program	Establish cooperation with partnering organizations and invite alumni to participate in the ISU ChipSat Program steering committee. Invite them to provide funding for development of the laboratory facilities for student Thesis and Individual Projects Provide training to staff members to provide an educated learning environment and take advantage of the research grants available
	Regulatory Framework	Lead AttoSatellite symposium to seek solutions to space debris mitigation and prevention

As all the elements of the Roadmap are interconnected and are happening in parallel, the schematic in Figure 5.2 below, illustrates this context for the reader. Only the key activities involved in the ISU ChipSat Program and Outreach Program are shown. The Regulatory Framework activities will support the ISU ChipSat mission but have not been shown in this image.

There are two proposed ChipSat missions, however, the priority is the ISU ChipSat mission developed through the ISU ChipSat Program. The secondary AmbaSat mission will occur first but will be managed by AmbaSat but will act as opportunity for ISU to develop the necessary skills and knowledge required for the ISU ChipSat Program The AmbaSat mission can also form part of the Outreach Program, although it is not essential for its success.

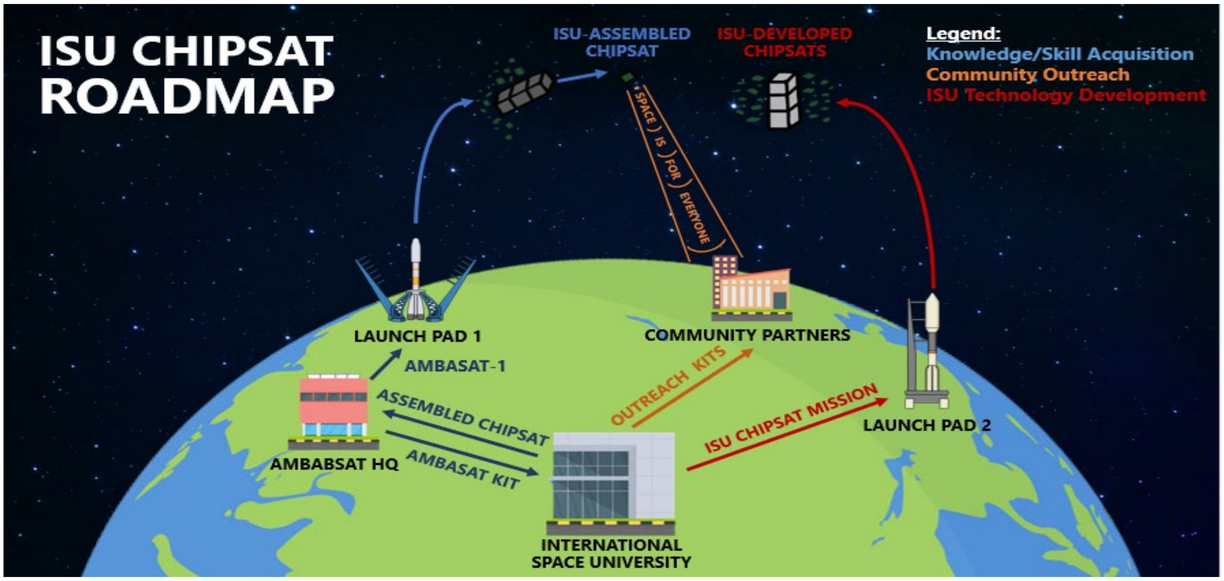

Figure 5.2. ISU Roadmap summary

5.3 ISU ChipSat Program

This chapter lists the steps required to set up the knowledge base and facilities to provide ISU with the capability of launching its own ChipSat within five years, and continuing to launch them in the future. It covers the technical aspects pertaining to the enhancement of ISU's capability and education programs through the ISU ChipSat Program. It is recommended that the ISU ChipSat Program be managed within the existing ISU Space Payload Laboratory structure.

The proposed activities for this segment of the ISU ChipSat Roadmap are summarised in Figure 5.3 below.

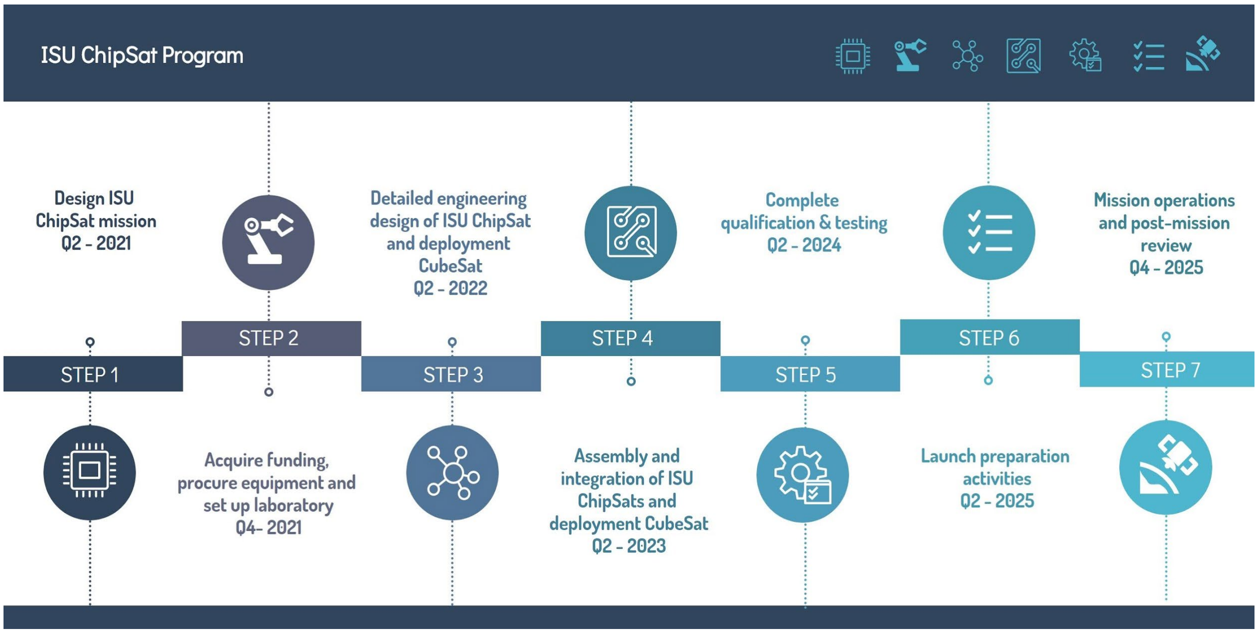

Figure 5.3. ISU ChipSat Program steps

5.3.1 Program Objectives

The key objectives of the ISU ChipSat Program are described below.

1. Develop a ISU ChipSat Mission to launch ChipSats to LEO within five years
   i. Educate students on ChipSats and provide hands-on, industry-relevant experience in space development cycles in the pursuit of launching the ISU ChipSat Mission
   ii. Develop technologies at ISU and build capability to work towards more advanced ChipSats in the future

2. Develop the necessary facilities at ISU for the on-going design and development of more advanced and capable ChipSats

5.3.2 ISU ChipSat Mission

The ISU ChipSat Mission development entails creating the basic hardware and software, as well as setting the foundation for future research. The objective of the first mission is to achieve a 'Sputnik-style' "beep" to communicate with a ground station from LEO. This objective is based on the following boundary conditions:

1. Compliance with the approximate weight of 10 grams as per the definition of a ChipSat, though initial iterations may fall above this mass (up to 25 grams)
2. State of available components and associated TRLs
3. Component operating limitations
4. Alternative component option availability
5. Synergy in both subsystem and component interaction

5.3.2.1 Project Lifecycle

The mission design and implementation will follow the required project lifecycle phases:

1. System Requirements Review (SRR)
2. System Design Review (SDR)
3. Software Specification Review (SSR)
4. Preliminary Design Review (PDR)
5. Critical Design Review (CDR)
6. Test Readiness Review (TRR)
7. Production Readiness Review (PRR)

Figure 5.4 below illustrates the typical development lifecycle used in space projects. This is important for students to gain experience with during their studies at ISU, and will be integral to the ISU ChipSat Program.

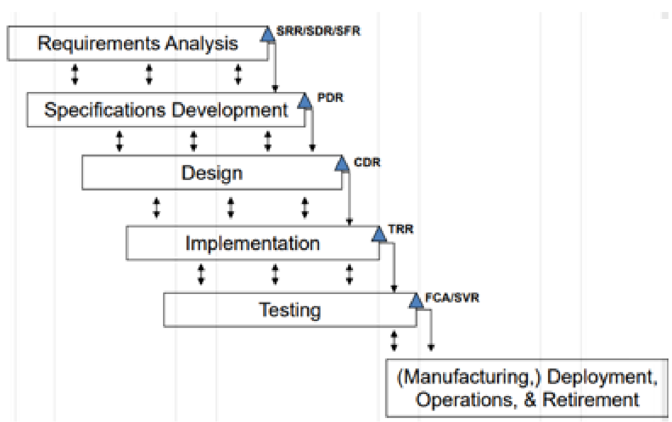

Figure 5.4. Development lifecycle (MacCarthy, 2006)

5.3.2.2 Key Technology Development

It is recommended for ISU to focus on developing the following key technologies

1. Mission software
2. PCB design
3. Power management and distribution
4. Communication with the antenna and ground station

Each of the above categories are explained as follows:

1. Mission Software

Design and implement mission software that will enable the education of students with relevant methodologies, processes, standards, and tools that are typically employed to develop spacecraft mission management software. The development of mission software will require a thorough familiarity of the TI CC430 Microcontroller, and the relevant C / C++ development environment.

It is recommended that three individual projects be allocated to software engineers (one lead and two contributors) during the first ISU ChipSat Program year, with the following master objectives:

1. Establish the development environment, perform integration, have an extensive familiarity of the TI CC430 Microcontroller functions and capabilities
2. Establish mission required documents and other software required documents
3. Develop the mission software, compile it, run and perform full tests, including debugging
4. Complete documentation of the software

It is recommended one individual project be allocated to a software engineer during the second and third-year phases with the following objectives:

1. Get familiar with the required documents, software development environment and software code
2. Enhance the code and support other development progress and required integrations

2. PCB Design

To support the long-term development of more advanced ChipSats, it will be required to have a PCB designed in-house. It is recommended to allocate, during the second year of the ISU ChipSat Program, an electronic engineer who will produce the initial PCB design with an eye toward potential upgrades in the future, such as payload/sensor and more advanced communications.

3. Power Management and Distribution

Develop the ability to use the solar array power generating component to power the TI CC430 Microcontroller, and other components in the future. It is recommended that an electronic engineer is tasked in the second year of the ISU ChipSat Program to make this design and execute implementation in the laboratory environment.

4. Communication

Capability and interfacing development of both the antenna and the microcontroller is required. Subsequent protocols and communication interfacing strategies with a ground station will need to be established. An additional electronic engineer will be required during the second ISU ChipSat Program year to derive this design and implement accordingly in the laboratory environment. Future enhancements may include ChipSat inter-communication.

A summary of the aforementioned activities for the roadmap have been summarized in Table 5.2.

Table 5.2. Annual technology development activities

	Year 1	Year 2	Year 3	Year 4
Mission Software	Software development Infrastructure **3 IPs** Skills: Mandatory: C / C++ Optional: Energia	**1 IP** Skills: Mandatory: C / C++ Optional: Energia	**1 IP** Skills: Mandatory: C / C++ Optional: Energia	**1 IP** Skills: Mandatory: C / C++ Optional: Energia
PCB Design		**1 IP** Mandatory: Knowledge in electronics		
Power Management and Distribution		**1 IP** Skills: Mandatory: Knowledge in electronics		
Communication		- Ground station integration - ChipSat Integration **1 IP** Skills: Optional: Knowledge in communication protocols		
Laboratory integration	**1 IP** Skills: No special requirements specified			
ChipSat integration			**1 IP:** Optional: Knowledge in electronics	**1 IP:** Optional: Knowledge in electronics
CubeSat integration & release mechanism			**1 IP:** Integration and deployment planning Skills: Knowledge and experience with small satellite component integration	**1 IP:** Integration and deployment implementation Skills: Knowledge and experience with small satellite component integration

5.3.2.3 ChipSat Platform

A preliminary component shortlist has been shared in Table 5.3 and outlines the relevant hardware characteristics. Figure 5.5 informs the mass budget of the selected components.

Table 5.3. Component shortlist specifications (Digi-key electronics, 2020; Mouser, 2020)

Component name	Mass (mg)	Size (mm^2)	Power (mW)	Temperature range	Price (EUR)
CC430 (CC1101 + MSP430)	140	49	50	-40°C +85°C	7.00
PCB FR-4 with Kapton tape	4000	2500	N/A	-50°C + 110°C	1
Passive components (resistors, capacitors, oscillators)	1000	1000	20	-55°C + 155°C	6
4x Photovoltaic cell TASC	1600	1000 x (2)	80	-40°C - 125°C	Unknown
Antenna: Ni-Ti flexible antenna V-shaped omnidirectional	1000	N/A	N/A	N/A	Unknown

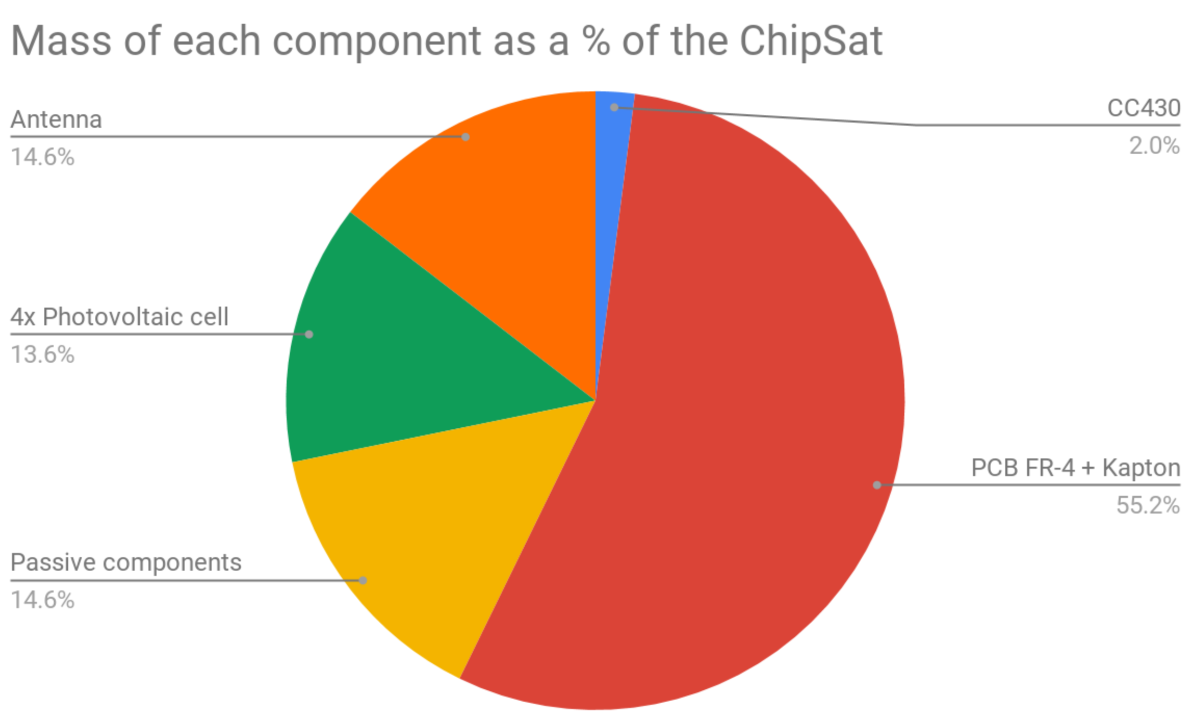

Figure 5.5. Count of component mass

The most fundamental component of the ChipSat is the CC430; a low power microcontroller which combines the functionality of a CC1101 and MSP430 chips. It has a power consumption rating of 160 µA/MHz in Central Processing Unit (CPU) active mode, and 2.0 µA in standby mode. Furthermore, the microcontroller can be powered off while retaining data stored in the Random Access Memory (RAM) and only consuming 1.0 µA of power. The CC430 microcontroller consumes 15 mA of power when transmitting data at a rate of 250 kbps at 915 MHz. The selection drivers behind this microcontroller are capabilities, power consumption, ease-of-use, community support, and TRL. The CC430 has already seen successful application on the Sprites platform for the KickSat missions and has been classified with a TRL level of 9. The 16-bit microcontroller can run at a CPU speed of up to 25 MHz, thereby, making it more than capable of reading simple sensor data and transmitting via the integrated radio module. A fundamental characteristic of the CC430 is the ability to be programmed using the C/C++ language through the open-source Energia Integrated Development Environment (IDE). IDE is based on the wiring framework and is compatible with most Arduino libraries, guaranteeing large community support. Furthermore, the Energia IDE features cross-platform support, including Linux, Mac Operating System (OS), and Windows OS.

In terms of platform design, a simple and miniaturized PCB structure employing COTS components should be sufficient to facilitate the achievement of mission objectives while keeping fabrication costs down. See Figure 5.6 below for ChipSat design.

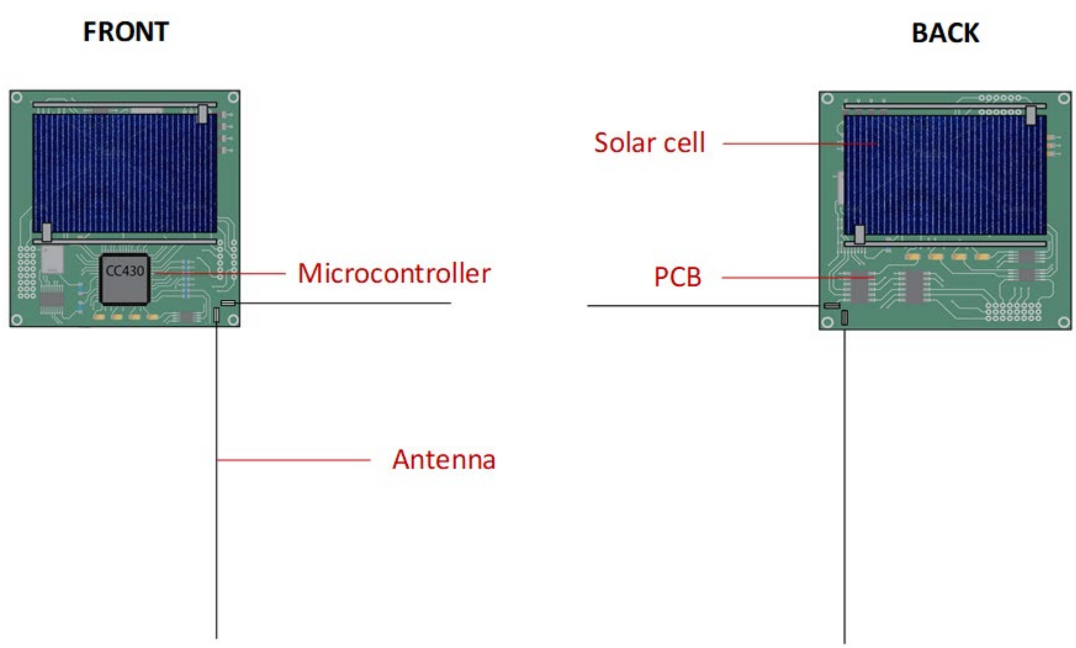

Figure 5.6. ChipSat design (front and back view)

For the design of the PCB, one needs to ensure all components are available including COTS items, sensors, and the microcontroller. A useful document to capture this is the creation of a Bill of Materials (BOM). Before the design can commence, these components should be tested, both separately, and as a fully integrated system, including bread-board testing. Once the final electrical schematic is achieved through an iterative process, one can start creating the PCB. It is advised that an experienced electronics engineer be tasked with facilitating the PCB design process.

The process of how to design a PCB layout has been described below. To design a PCB, it is advised to create a schematic of the circuit to be manufactured. For this, it is required to have the necessary libraries of the components to be used.

A library presents the main physical, electrical and geometric characteristics of a component that will be placed in the printed circuit and it allows us to have a graphic representation of the composition both in the schematic and in the design of the board. By containing the most relevant information about it, it facilitates the spatial visualization of the component during the design, allowing an avoidance of errors, such as the lack of spacing between components.

Subsequently, the schematic can be performed. A schematic is a representation of how the components of an electrical circuit are connected and are created by the designer of the device. A good schematic contains virtual cables and graphics or footprint of each component, indicating what kind of device it is, for example, a resistor, capacitor, inductor, diode, among others.

Finally, the PCB is designed. The outline is the line that indicates the boundaries of the board. The card designer (electronic engineer) is the one who defines the impedances used in the card, making transmission lines of known impedances to reduce the reflection of the signal, especially at high frequencies. The impedance of the strokes is defined by certain physical geometries such as width, length, and shape. For high frequencies, impedance control strokes can be drawn: microstrip and strip lines. The former (to transmit microwave signals) consists of a line that is on a ground plane, where between them there is a dielectric material. Strip lines - transmission lines for Transverse Electromagnetic (TEM) modes are like microstrip but with ground planes above and below it (equally separated by dielectric materials).

After the card design, it is manufactured. The Institute for Interconnecting and Packaging Electronic Circuits (IPC) carries out standards on the assembly and production of electronic equipment, thus establishing the general manufacturing rules. It is important to properly define the manufacturing rules because it helps reduce costs by minimizing errors and processes since the validation of electrical connectivity, assembly, testing, the separation between parts, electromagnetic compatibility, etc. is defined.

5.3.2.4 Payload Proposal

Five payload candidates have been proposed for ISU to take into consideration for future missions. Due to the 10-gram mass constraint of a ChipSat, the list of payloads and sensors are primarily MEMS-based. Table 5.4 lists these candidates with their associated properties; size, TRL, and applications. Among all these payload options, the magnetometer, Ultraviolet (UV) sensor and the accelerometer have better TRL levels and can be easily integrated in the ISU ChipSat.

The test using an EDT for propellantless propulsion suggests deploying conducting wires from a ChipSat to interact with the Earth’s magnetic field. Another ChipSat would be attached at the other end acting as a paired mass for attitude control and stability. An EDT of 3 to 10 meters in length could provide sufficient thrust for a 1 to 100 gram satellite to overcome the drag forces found in low-Earth orbit (Burkhardt, 2019). While this concept possesses a low TRL, due to the low cost and redundant nature of chipsats, they remain the most suitable candidate for EDT technology demonstration.

Table 5.4. Proposed payload options for ISU ChipSat

Payload	Size(mm)/ Mass(g)	Application	TRL	References	Sourced From
Magnetometers	Size : 3x3x0.9 Mass: 1.8	E-compass - Estimates of attitude and also orbital position	9	(Honeywell, 2013)	Europe
Accelerometer	Size: 3x5x1 Mass: Unknown	Measures acceleration, tilt, shock, and vibration in ChipSat missions. To measure the deceleration due to atmospheric drag	9	(Freescale, 2008)	Europe
UV Sensor	Size: 20x18x2 Mass: 1.4	UV Index Monitoring	7	(Adafruit, 2020)	Europe
Spectrometer (Pc-slab Spectrometers)	Size: 18x18x49 Mass: TBD	Imaging	4	(Happich, 2017)	Unknown
Seismic Sensor (Mems Seismometers)	Size: 11.3x11.3x1.2 Mass: 1	Can Detect Vibrations In All Three Spatial Directions Seismic activity, cryo-volcanic activity, and the frequency of meteoric impacts	4	(Seis Insight, 2016) (Jet Propulsion Laboratory, 2019)	Europe
EDT Test For Propulsion	Length: 3000-10000 m Mass: Unknown	Attitude control using magnetic field Provide sufficient thrust for a 1 - 100 g satellite to overcome LEO drag	3	(Bell et al., 2013)	Unknown

5.3.2.5 CubeSat Deployment

A valid example of ChipSat deployment has been carried out by the KickSat-2 spacecraft, seen in Figure 5.7. KickSat-2 is a 3U CubeSat where one of the units serves as a platform, and the other two are dedicated to housing and deploying the Sprites (Manchester et al., 2013). CubeSats represent an excellent option for ChipSat deployment. CubeSats can deploy hundreds of ChipSats at a time, although the nature of the deployment is expected to be coarse. Spring-loaded mechanisms can represent a relatively simple option for CubeSat-based deployment, but the mothership will likely have little control over where each ChipSat will go. This deployment methodology can be effective when a large area of interest is targeted and, therefore, precise deployment direction is not required.

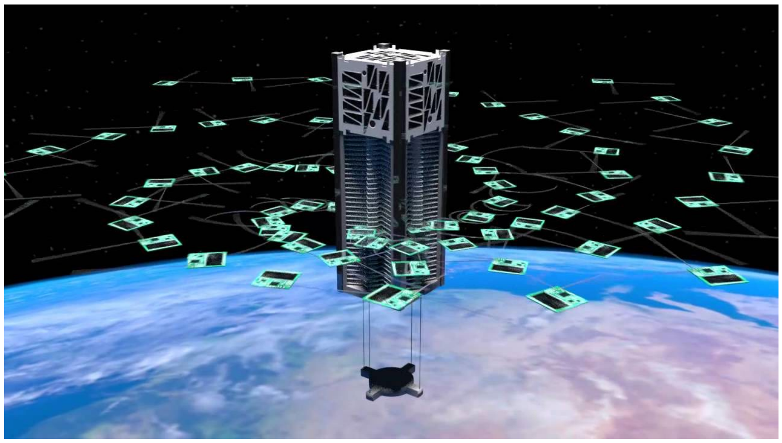

Figure 5.7. The CubeSat KickSat-2 LEO Deployment of Sprites (Manchester, 2013)

Simplicity and robustness were key points during the development of the Sprite deployer. Another element of high attention was the minimization of the attitude disturbances during deployment. Using a carbon fiber rod, a Sprite was put in an individual compartment. The deployment itself was performed with the help of the nitinol wire antennas, since the way they were coiled was replicating a spring system. All Sprites were connected to a plate at the end of the CubeSat. That plate was actuated by a spring that was held in place by a locking mechanism. That mechanism unlocked after a nichrome burn wire was triggered, resulting in the deployment of the Sprites with an estimated delta-V of 5-10 cm/sec (Manchester, Peck and Filo, 2013).

The top-level requirements for the deployment mechanism:

1. The deployment mechanism shall be simple and robust
2. The deployment mechanism shall minimize attitude disturbances during deployment
3. The deployment mechanism shall constrain each ChipSat individually (using a rod)
4. The deployment mechanism shall allow for a release velocity (delta-V) of about 5 to 10 cm/sec

The CubeSat deployer could be launched on a rocket or alternatively deployed from the International Space Station. This decision will depend on the launch opportunities available at the time.

5.3.3 ISU ChipSat Facilities

A dedicated workplace is required to facilitate the development of ChipSats at ISU. Despite ChipSats being smaller and less complex than any other satellite, they will still require specialized equipment to support assembly, integration, and testing.

This chapter takes stock of the existing facilities at ISU that can be used to support ChipSat development and presents a shortlist of items, which are recommended for purchase with the expected costs. The proposed structure involves adaptation to two existing facilities at ISU, the Make-It-Space and ISU Payload Laboratory, which together will form the ISU ChipSat Laboratory.

The setup of the proposed ISU ChipSat Laboratory is projected to be completed by the end of 2021. The laboratory and testing facility will be based in the ISU building. However, if the listed equipment is beyond ISU's financial reach, establishing a cooperative arrangement with other universities for equipment sharing is encouraged. The benefit of having an in-house laboratory is the potential reduced costs and all-round availability compared to outsourcing ChipSat assembly at other institutions. Furthermore, a home-grown knowledge base on ChipSat assembly and testing can benefit the ISU curriculum by teaching students in a simulated environment using the tools used in typical satellite manufacturing. The production of a ChipSat may also form a strong basis for inter-institutional collaboration given some universities already have all the necessary equipment to support ChipSat development.

5.3.3.1 Current ISU Facilities

There are two facilities at ISU that are a suitable starting point for the proposed ISU ChipSat Laboratory.

1. Make-It-Space: Located on the second floor close to the academic pod
2. ISU Payload Laboratory: Located on the second floor adjacent to the CDF

The ISU ChipSat Laboratory will support the design, integration, and testing of individual components, before conducting the final assembly, qualification, and testing of ChipSats.

The ISU Payload Laboratory is equipped with a dedicated computer used for programming, circuit simulation, and editing. Created Gerber files can be later sent to a PCB manufacturer. During the testing phase, variable power supplies can be used to provide the required voltage and current for the system before an onboard power source is integrated.

ISU's facilities have tools suitable for working with PCB plates and electric chains. All equipment necessary for soldering is available in the Make-It-Space, which is equipped with a range of soldering irons, a stock of expendables, such as rosin and tin, and a set of advanced tools to ensure the correct work of an electrical chain:

1. Multimeter (used for measuring voltage, current and resistance, etc)
2. Step-down transformer (used for creating a steady current)
3. Stable power supply

Additionally, the ISU Payload Lab has some key tools required for working with small electric circuitry:

1. Static shielding bags
2. Special static wristbands
3. Wave generators

4. Oscilloscopes

During breadboard or PCB testing, the use of an oscilloscope will be necessary to display the behavior of electronic signals over time. This instrument enables signal visualization, measurement, and comparison across respective amplitudes, frequencies, and duty cycles.

In addition to hardware testing and validation, ChipSats must successfully pass milestone tests before being granted launch approval. There are two options to solve this issue:

1. Establish an ISU-based facility. This will contribute to ISU's capabilities of creating and testing its own satellites in a cost-effective manner. This option will demand larger capital investment which can pay off over the long-term
2. Outsource testing activities to other institutions. This will provide a new topic for inter-institutional cooperation. Examples of testing activities include soak tests, vibration tests, deployment, and thermal vacuum tests

While ISU is equipped with some basic tools for working with ChipSats, it is currently not equipped with required to build, integrate, test and qualify ChipSats. Although, the above mentioned equipment can be used to set the foundation for the laboratory. The development team will require sets of facilities at each project phase including fabrication, assembly, integration, test, and in-orbit operation. Also, there is no setup in place to facilitate the work for the ChipSat electronics. A clean room environment is not mandatory for ChipSats, although it is often used in a standard satellite laboratory.

ISU has previously received laboratory support from the University of Strasbourg and École Catholique d'Arts et Métiers (ECAM) for payload development initiatives, such as the Hydra payload. During the ChipSat implementation phase of the proposed Roadmap, the current laboratory facilities and testing potential of ISU will need to be improved to ensure high-quality integration and testing.

The facilities of other universities involved in the KickSat project were reviewed to assist with forming the equipment requirements for the ISU ChipSat Laboratory. The research facilities at Stanford University, Cornell University, University of Surrey and University of Illinois have been studied as model examples to inform a proposed set of facility requirements to enable ChipSat testing. The founder of the KickSat project, Zac Manchester, mentioned during a teleconference call held with the project team on 7 February 2020 the laboratory requirements for building ChipSats are very basic and similar to a typical electronics laboratory. It was said that the presence of electric test benches and grounding facilities is enough for integration of ChipSats (Manchester, 2020).

The following supportive infrastructure have been recommended to bolster the existing laboratory setup at ISU. The following section identifies the various testing facilities which are required for functional and qualification tests of ChipSat. It also includes the optional test facilities which are recommended to be outsourced in case such tests are required to comply with the launch provider's requirements.

5.3.3.2 Proposed ISU Facilities Modification

As the foregoing suggests, ISU already has most of the tools necessary for the production of a ChipSat, however, the organization of a dedicated workplace is desired. All the tools are evenly distributed between the Make-It-Space and the ISU Payload Laboratory, implying the need for a constant exchange of tools between these facilities. To solve this issue, the following measures are recommended:

1. To clearly distinguish operations that are done in both facilities and to place required tools in a dedicated facility
2. To purchase another piece of equipment, if the same tool is required for both facilities

Currently, the Make-It-Space nor the ISU Payload Laboratory have a dedicated working place suitable for working with small PCBs and micro-circuits. However, the ISU Payload Laboratory is the superior option for the majority of the required ISU ChipSat Laboratory activities. The Make-It-Space typically facilitates woodwork and metalwork activities which are prone to producing fine dust. Fine dust can spoil electronic circuitry and the required clean space for ChipSat assembly and testing.

The ISU ChipSat Laboratory workstation has to conform to certain parameters. Given the scale of a ChipSat, the soldering and assembly process of a ChipSat will demand precise motor skills paired with high levels of concentration. To facilitate this, the workstation must be well illuminated and ideally possess spot lamps that can be adjusted to light up specific areas of the table. Equipping the workstation with a dedicated set of solder clamps (i.e. the third arm) and a high-quality magnifying glass are highly desirable; both would contribute to delivering a higher quality product following assembly. These items can be found in the Make-It-Space, however, they do not have mounts. In terms of air safety, a directed ventilation hose will safely remove smoke from soldering while also keeping the ChipSat clearly visible during the work process. Cable harnesses and a soldering station equipped with lenses, irons, an electronic bench with grounding facility are required to remain aligned with the quality standards stated by International Organization for Standardization (ISO) (Nieto-Peroy and Emami, 2019).

5.3.3.3 Required Equipment

The ISU Payload Laboratory can serve as the central hub for all ChipSat related activities, including manufacturing, component storage and assembly. An additional laboratory situated on the ISU ground floor can be employed as a cleanroom facility.

The following test facilities are required for implementation of the ISU Roadmap:

1. Functional Test Facilities
2. Qualification Test Equipment
3. RF Range Test and Ground Station Facility

Functional Test Facilities

Cleanroom conditions may not be mandatory during assembly, however they will be required to perform functional tests on the ChipSats. These tests would focus on assessing the basic functionalities of a ChipSat which help ensure a ChipSat performs as it should to achieve the mission objective. Functions pertaining to communications, power distribution, and fault management will be addressed during these tests. (Nieto-Peroy and Emami, 2019).

The cleanroom shall be equipped with grounded anti-electrostatic-discharge mats, electrostatic wristbands, a computer, multimeter, function generator, power supply, and oscilloscope for integrating electronic components and associated functional tests. For example, power distribution will be tested by configuring the ChipSat to its routine operations mode and a multimeter will be applied to check the appropriate power is being allocated to each component. Most functional tests for ChipSats can be performed in a cleanroom but for qualification tests, ISU will require specialized mechanical test facilities as shown in Figure 5.8 below.

The ISO guidance recommends a cleanroom standard of ISO-7 for working with electronics and sensitive components. Since regular office space, such as the interior of ISU, falls into ISO-9 cleanroom category, the application of an airlock between the hall and the cleanroom is required. The airlock must be equipped with a blower, which would provide increased pressure and can be connected to a ventilation system. There are commercially available solutions which can be mounted to any door. The company Terra Universal provides airlocks for both technical and medical institutions and have an established manufacturing line. The price for the basic airlock with a blower is $10,062 (Terra Universal, 2020). If ISU decides to create a cleanroom facility, it is recommended a cleanroom class of ISO-7 to 8 be obtained. For comparison, Airbus cleanrooms for communication satellites are of ISO-8 (cleanroom Technology, 2018).

Figure 5.8. Cleanroom facilities at the University of Illinois (Lynch, 2017)

Qualification Test Equipment

There are three major pieces of equipment that will be required to facilitate the qualification tests of the ISU ChipSats:

Electrodynamic Shaker

An electrodynamic shaker performs major mechanical testing such as sine vibration, resonance searching, and random vibration, as seen below in Figure 5.9. Based on the project research performed in other universities, the Ling 612VH electrodynamic shaker proved suitable, however, its substantial dimensioning might prevent it from being accommodated in ISU (Brummit, 2010). Further research shows that DuoBase-127 (DB-127) electrodynamic shaker is capable of providing sufficient stress, while being more compact that the Ling 612VH. The price of the shaker will be calculated individually based on ISU’s requirements and the existing suite of equipment. However, based on similar shakers available on the market, the price is estimated to be between $14,000 and $30,000. The average value of $22,000 has been used for the cost analysis.

Thermal Vacuum Chamber

This device is used to simulate the vacuum and temperature conditions ChipSats will experience in the space environment. Temperatures can vary between -40°C to +200°C. This is an essential test to ensure that satellites can survive the harsh conditions of space. To conduct the relevant bake-out test, a thermal vacuum oven is required. The thermal vacuum chamber can also be used for adhesive preparation and vacuum curing, as seen in Figure 5.9.

The LACO Technologies company specializes in organizing vacuum-related industry-level facilities that have been used in projects by NASA and other space companies. They have a variety of vacuum chambers which can be upgraded to thermal vacuum chambers. The proposed option is the thermal vacuum chamber, based on the 20" Cube High Vacuum Chamber. The price of this piece of equipment is approximately $2,500.

It should be noted these test facilities are expensive and will add significant cost to the ISU Roadmap implementation process. As such, ISU should consider outsourcing testing to ESA’s CubeSats Support Facility as a viable alternative.

Electromagnetic Compatibility (EMC) Test Facility

EMC is a vital element to be considered in the ChipSat system design. The design is constrained by size and mass, which poses a significant challenge to shielding sub-system components from the degrading electromagnetic space radiation environment. An example of an EMC test facility is shown in Figure 5.9.

We recommend ISU outsource this facility as opposed to purchasing. Aside from the test facilities at ESA's ESTEC, private companies such as Innovative Solutions in Space (ISIS) (Innovative Solutions in Space, 2020) and Sun Fire Testing (Sunfire Testing, 2020) offer EMC test rigs for small satellites. To support electromagnetic interference detection, a spectrum analyzer with variant frequency ranges will be required.

Figure 5.9. a) Qualification Test Equipment: Electrodynamic Shaker b) Thermal Vacuum System c) Electromagnetic Compatibility (EMC) test facility (Labworks Inc., 2020; LACO Technologies, 2020; ISIS, 2020)

RF Range Test and Ground Station Facility

ISU ChipSat Mission will rely on one ground station to send telemetry. A ground station suitable for a simple mission for educational outreach purposes typically uses amateur radio frequencies in the range of 430 - 440 MHz. The ground station antennas need to be installed in an open area to avoid harmful interference. ISU has a ground station facility operating in VHF and UHF bands which can be used for the proposed ISU ChipSat Mission. Currently, ISU ground station is capable of only receiving/detecting satellite beacon signals in Continuous Waveform (CW) format. But for sending Telecommand (TC) or receiving Telemetry (TM), softwares needs to be upgraded. To validate ground system performance, RF range tests will need to be performed. For RF range testing, a standard PC with GNRadio software can be used (Manchester, 2015). ISU ground station is capable of supporting ISU ChipSat Mission in VHF and UHF frequency bands.

5.3.3.4 Optional Equipment

The optional test facilities cover the equipment and facilities that are not recommended to purchase to implement the Roadmap. Instead, it is recommended to collaborate with ECAM, University of Strasbourg, and European Space Agency (ESA) ESTEC to minimize the cost and outsource the following testing facilities based on the mission requirement.

Figure 5.10. Helmholtz Coil facility (University of Surrey, 2020), Moment of Inertia Measurement Device (Space Electronics, 2020), Center of Gravity Measurement Device (Lynch, 2017)

Helmholtz Coil

This equipment shown in Figure 5.10 is employed for calibrating magnetometers, testing magnetic torque coils, and attitude determination and control testing. This tool is used to test and calibrate magnetometers, coils, and other magnet-related equipment. The price of this equipment varies drastically from \$500 to \$57,500. However, the Helmholtz Coil can be outsourced to minimize cost. For testing ChipSats, a Helmholtz Coil of 150 millimeter diameter would suffice, but it is worth considering the plans of the university. If ISU plans to launch its CubeSat with ChipSats onboard, then it is worth purchasing a 500 millimeter which is capable of working with CubeSats. These coils are available for purchase from different manufacturers and further studies could reveal the best one. For this report, it is recommended to purchase the coil from GMW Associates, which specializes in magnet-related equipment. A 500 millimeter diameter three-axis Helmholtz Coil HC1-3 with a three-axis control unit CU1 and the relevant customer training would cost a total of $31,090 (GMW Associates, 2020).

Moment of Inertia Measurement Device

The Moment of Inertia Measurement Device seen Figure 5.10 can determine the inertia about the orthogonal body axes of a satellite or piece of hardware. The moment of inertia affects the dynamic characteristics of spacecraft. Accurate mass characteristic measurements are important to adequately control spacecraft attitude. As the proposed ISU ChipSat doesn't have an attitude control subsystem this is an optional facility for ISU Roadmap implementation.

Center of Gravity Calculation Device

The device shown in Figure 5.10 is used to measure the two-dimensional center of gravity of the satellite and the subsystems. From the 2D measurements, it is possible to determine the full 3D location of the center of gravity by taking three measurements in an orthogonal pair of directions. The device is used to get the necessary data for stabilization of the spacecraft.

It is possible to find a device which can combine the functionalities of a center-of-gravity calculation device and moment of inertia device. The company Space Electronics LLC produces both types of instruments, and for proposed projects, the Moment of Inertia Instrument XR50 was chosen. It works with objects up to 22.5 kilograms and costs $1,000 (Space Electronics, 2020).

Fabrication Facilities

ISU ChipSat will be built on standard PCBs using COTS components. Hence, fabrication should not be required. Therefore, extensive fabrication and structural development facilities are not a mandatory requirement for ISU ChipSat Laboratory.

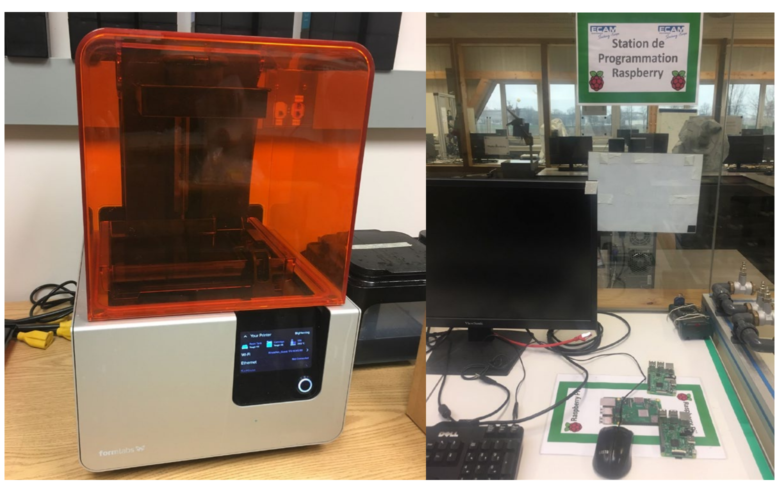

Figure 5.11. CNC machine to produce satellite parts and fixtures for testing (Lynch, 2017), Raspberry Pi programming station at ECAM (original photo)

However, to facilitate rapid component prototyping, a computer numerical control (CNC) machine and an additive manufacturing machine will need to be incorporated as additional instruments to the laboratory, seen in Figure 5.11. ISU already has a CNC machine to support the fabrication of simple structural elements, and to perform minor modifications to the existing hardware. In addition, ECAM has a complete electronics laboratory setup with a CNC machine, 3D printer along with the facility for programming the PCBs like raspberry pi, seen in Figure 5.11 above. This facility could also be used by ISU.

Radiation Hardness Test

Radiation testing is an important element for ChipSats both technically and in terms of safety regulations. Lapses in the appropriate radiation testing and analysis increases the mission risk (Campola and Pellish, 2019). As ChipSats mostly use COTS components, the component level assurance against radiation hardness is an important issue. This is related to the lessons learned from the KickSat-1 project launched on 18 April 2014. The 104 ChipSats onboard KickSat-1 failed to deploy due to cosmic radiation bursts. Consequently, the spacecraft fell out of the orbit and burned up the atmosphere without achieving its mission goals (Jones, 2016). Hence, radiation hardness assurance is a key requirement to understand the survival capability of ChipSats in the radiation exposed environment of space across the duration of the mission lifetime (Campola and Pellish, 2019).

A radiation test facility is capable of subjecting different forms of radiation to a ChipSat. The ESTEC radiation test facility, Cobalt-60, is a suitable candidate as it complies with the ISO-17025 testing and calibration standards, as seen below in Figure 5.12.

Figure 5.12. Cobalt-60 Irradiation Facility of ESTEC (ESA, 2020)

Similar to the thermal vacuum chamber, this facility is expensive to utilize. ISU may require the relevant licensing from the appropriate French Authority to operate this facility. In light of these factors, ISU is recommended to outsource the use of such a test facility from ESA.

5.3.3.5 Equipment Purchasing and Outsourcing Summary

Following on from the previous sections, the equipment, tools and software listed in Table 5.5 are recommended for purchase. Table 5.6 contains the equipment that can be outsourced, while Table 5.7 contains the optional equipment that would be useful, but not completely necessary.

Table 5.5. Recommended Equipment/Tools for the ISU Laboratory

Equipment/Tools	**Category**	**Availability at ISU**	**Recommendation**	**Approximate cost (USD)**
PCB design tools	Software	**Available** (‘Altium designer’)	Useful for PCB design	Already available
Multimeter	Hardware	**Available**	Useful for ChipSat IAT	Already available
Oscilloscope	Hardware	**Available**	Useful for ChipSat IAT	Already available
3D printer	Machine	**Available**	Useful for ChipSat IAT	Already available
Function Generator	Hardware	**Available**	Useful for ChipSat IAT	Already available
Variable Power Supply	Hardware	**Available** (upgrade required)	Need to purchase (Need regulated/variable power generation capability)	$600-$900 (Metrix Electronics, 2020)
Grounded workbenches	Machine/ Hardware	**Available** (update required)	Need to purchase (for soldering and testing components)	$150 and above (Deutsch, 2012)
Circuit simulator	Software	Not available	Need to purchase	$100-600
Schematic editor	Software	Not available	Need to purchase (professional version)	$700-800 (Marrakchi, D., 2016)
Clean room airlock (with a blower)	Hardware	Not available	Need to purchase for cleanroom condition	$10,062 (Terra Universal, 2020)
TOTAL (for purchase):				**~$15,000**

Table 5.6. Recommended Equipment/Tools for Outsourcing

Equipment/Tools	**Category**	**Availability at ISU**	**Recommendation**	**Approximate cost (USD)***
Thermal Vacuum Chamber, based on 20" Cube High Vacuum Chamber	Machine/ Hardware	Not available	Can be outsourced	$2,500 with temperature control) (LACO Technologies, 2020)
Electrodynamic Shaker DuoBase-127 (DB-127)	Machine/ Hardware	Not available	Can be purchased or can be outsourced	$22,000 with 3-axis vibration (Labworks Inc., 2020)

EMC testing facility	Machine	Not available	Can be outsourced	Starting $1000 (Sunfire Testing, 2020)
Radiation Test Facility	Machine	Not available	Can be outsourced	Depends on the terms of an agreement
Total (outsource):				**~$25,000** (excl. Radiation test)

*Outsourcing cost might vary based on Request for Quotation

Table 5.7. Optional Equipment/Tools for ISU Laboratory

Equipment/Tools	Category	Availability at ISU	Recommendation	Approximate cost (USD)*
Computer Numerical Control (CNC) machine	Machine	Available	Optional Item	Not applicable
Moment of Inertia Measurement Device XR50	Machine	Not available	Optional item (Not required to purchase)	$1,000 (Space Electronics, 2020)
Center of Gravity Calculation Device	Machine	Not available	Optional item (Not required to purchase)	Yet to be determined (not available online)
3-axis Helmholtz Coil HC1-3	Machine/Hardware	Not Available	Optional item (can be outsourced)	$31,090 (GMW Associates, 2020)

*Purchase cost might vary based on Request for Quotation

ISU is currently equipped with the basic tools necessary for building a ChipSat and manufacturing certain components. ChipSats do not require advanced or complex testing facilities however acquiring the necessary equipment will still require a reasonable financial investment from ISU.

5.3.4 ISU ChipSat Program Conclusion

ISU ChipSat Program is the key to educating the students in the relevant technology and development lifecycles, while developing technologies and expertise within the institution. This will be enabled by the establishment of suitable facilities within ISU.

The ultimate goal is for ISU to launch its own ChipSats within five years, and this can be achievable by following the steps outlined in this section. ISU ChipSat Program will be managed by the Space Payload Laboratory and open opportunities to apply for funding for scientific research, technology development and missions.

5.4 Legal Challenges for ISU ChipSats Roadmap

ISU ChipSat Mission will not only be a challenge from an engineering perspective, but it will also be a significant legal challenge. This view is shared by Zac Manchester, who already launched ChipSats in 2017 and emphasizes that the biggest challenge will be adaptation the regulations to these very small satellites (Manchester, 2020).

ChipSats are a new disruptive technology for which the existing international and national legal framework is not tailored. There is no universally accepted definition for how small a small satellite is (United Nations Office for Outer Space Affairs and International Telecommunication Union, 2015).

All the policies mentioned hereafter refer to small satellites, but none of them mention ChipSats. This report will provide an overview of the legal and regulatory challenges that need to be overcome for successfully planning and launching an ISU ChipSat Mission. It will focus on registration, licensing, international and national frequency allocation through Agence National des Fréquences (ANFR) and the ITU, legal requirements under the French Space Operations Act, and end-of-life mitigation. Planning ISU ChipSat Mission will also require other legal aspects such as intellectual property consideration, contracts with suppliers, compliance with international space treaties and export control rules that will not be discussed in the report but should be examined. Further discussion on these topics can be found in the Literature Review document.

The regulatory activities required for ISU ChipSat mission are summarized in Figure 5.13 below.

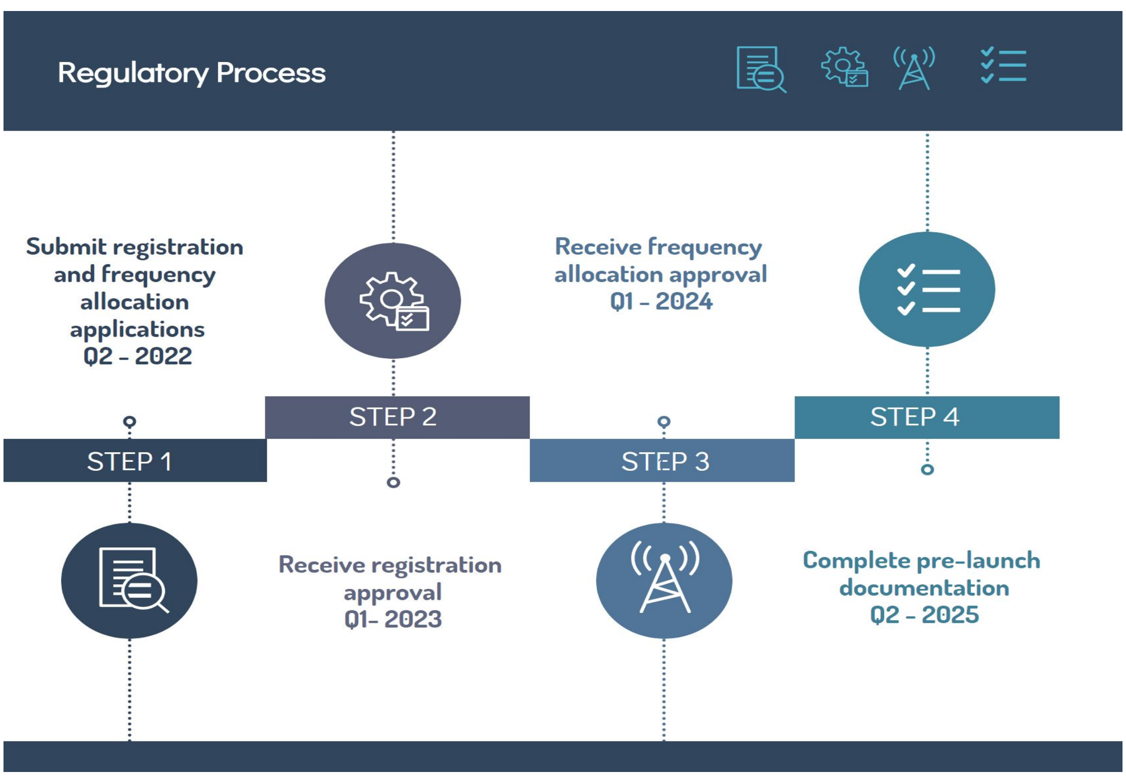

Figure 5.13. Regulatory Process for ISU ChipSat Program

5.4.1 Registration and Authorization with Centre National D'Etudes Spatiales (CNES)

When considering the ISU ChipSat Mission, the first legal step will be to determine who is the appropriate State of Registry, and where ISU will need to start the procedure for licensing. The main legal instrument in France is the 'Loi relative aux Opérations Spatiales de 2008' (French Space Operation Acts 2008) (LOI no 2008-518 du 3 Juin 2008 relative aux opérations spatiales).

The satellite needs to be authorized by the French Ministry of Space, the procedures are explained in the "Décret d'application" of 9 June 2009 (Décret n° 2009-643 du 9 juin 2009 relatif aux autorisations délivrées en application de la loi n° 2008-518 du 3 juin 2008 relative aux opérations spatiales, 2009). There are administrative and technical documents that must be filed and send to the Minister of Space (Arrêté du 31 Mars 2011 relatif à la réglementation technique en application du décret n° 2009-643 du 9 juin 2009 relatif aux autorisations délivrées en application de la loi n° 2008-518 du 3 juin 2008 relative aux opérations spatiales).

This process aims at obtaining the authorization of control over the space object in space. However, the technical regulations do not oblige the operator, in this case, ISU, to effectively maneuver the satellite (Mariez, 2020). Proving that ISU can communicate with the satellite is sufficient. There have been small educational satellites in the past approved by France under these criteria (Centre Spatial Universitaire de Montpellier, 2020).

There are two main technical points to tackle for authorization. The first one is the obligation to take insurance to cover third-person liability up to €50-70 million, or $56-79 million (Article 6, LOI no 2008-518 du 3 Juin 2008 relative aux opérations spatiales). The French Space Operation Act requires any operator conducting space activities to take insurance. The French regime on liability and insurance for space damages is well defined. If the damage is caused by the fault of the victim or the operator was not negligent and adhered to a license, the liability could be elapsed.

The second point is the obligation for the satellite to automatically de-orbit before 25 years and re-enter the atmosphere to burn up (Arrêté du 31 mars 2011 relatif à la réglementation technique en application du décret n° 2009-643 du 9 juin 2009 relatif aux autorisations délivrées en application de la loi n° 2008-518 du 3 juin 2008 relative aux opérations spatiales, 2011). This aligns with the Space Debris Mitigation Guidelines (United Nations, 2010). ISU needs to take both of these technical points into account when preparing for an ISU ChipSat Mission.

There are currently no adapted regulations for small satellites so they must follow the same filing procedures and fulfill the same insurance requirements as a large satellite from EUTELSAT, for instance. However, since the Roadmap has a plan for five years, it is important to mention that CNES is currently updating the entire French Space Act to better handle new challenges, particularly surrounding small satellites. A lighter procedure will be expected and less insurance, as well as technical requirements, will be needed for small satellites. This is promising for ChipSats at ISU and also other educational and small satellites in France.

If ISU wants to pursue the Roadmap and develop commercial missions consisting of constellations, this should be addressed and made easier by the updated regulations. As shown below in Figure 5.14, this new set of rules should be ready within the next two years. Then, once the satellite is in orbit, the operator, in this case, ISU, should inform the CNES of any problems. It should also inform CNES on orbital parameters and technical specificities for CNES to officially register the space object. ISU, as the operator, through France, will exercise jurisdiction and control over the ChipSat, under the LIAB (Convention on International Liability for Damage Caused by Space, 1972).

Timeline: 6 months

Step 1	Contact CNES when the design is ready
Step 2	Start the procedure
Step 3	Send the request to the Ministry of Space
Step 4	Approval from the Ministry of Space
Step 5	Inform CNES of any problems during satellite life
Step 6	Once in orbit, give information for registration
Step 7	Registered under French National Registry – ISU has Jurisdiction and control

Figure 5.14. Steps for ISU ChipSat mission to request authorization and register the satellites in France

Overall, the process of requesting authorization, licensing and registration from the French Ministry of Space and CNES is well explained within the different regulations. Support is provided by the CNES department in charge of the French Space Operation Act application based in Toulouse, and the process is free of charge in France. This is a real advantage when considering ISU ChipSat Mission. However, the regulations are not yet tailored for small satellites therefore insurance fees and technical requirements might be challenging. Yet, the new upcoming update of the regulations should tackle these constraints, which looks promising for a future ISU ChipSat Mission.

5.4.2 International and National (France) Frequency Allocation – ITU and ANFR

Before launching a ChipSat, ISU will have to carefully take into consideration the coordination of frequency allocation and allotment to avoid RFI and disruptions from other satellites (Weeden, 2013). At the international level, the ITU supervises Frequency Allocation and Management. ITU regulatory frameworks include the ITU Constitution, Convention and the RR that define the frequency spectrum allocations and the rights and obligations of operators. In France, ANFR supervises the frequency allocation for space objects.

5.4.2.1 Educational Missions Using Amateur Frequencies

When preparing for the launch of an educational ChipSat mission, the procedure to request frequency is as follows. The first step will be to contact ANFR to start the procedure of filing a request for frequency.

As of February 2020, the team is already in contact with ANFR and the head of the Frequency allocation is happy to help start the procedure. An educational satellite typically uses amateur frequencies according to Article 1.56 and 1.57 of the RR (ITU, 2016). These categories describe an amateur frequency:

"*1.56 amateur service: A radiocommunication service for self-training, intercommunication, and technical investigations carried out by amateurs, that is, by duly authorized persons interested in radio technique solely with a personal aim and without pecuniary interest.*

1.57 amateur-satellite service: A radiocommunication service using space stations on earth satellites for the same purposes as those of the amateur service." (ITU, 2016).

An amateur frequency request also benefits from the International Amateur Radio Union support as well as CNES frequency department support for student projects.

The International Amateur Radio Union (IARU) has a guide to explain the process of requesting frequencies (see. Annexes "Amateur satellite frequency coordination request).

The center frequency is 425.5 MHz and bandwidth usually ranges between the and 387-464 MHz.

"5*.282. In the bands 435-438 MHz, 1 260-1 270 MHz, 2 400-2 450 MHz, 3 400-3 410 MHz (in Regions 2 and 3 only) and 5 650-5 670 MHz, the amateur-satellite service may operate subject to not causing harmful interference to other services operating in accordance with the Table (see No. 5.43). Administrations authorizing such use shall ensure that any harmful interference caused by emissions from a station in the amateur-satellite service is immediately eliminated per the provisions of No. 25.11. The use of the bands 1 260-1 270 MHz and 5 650-5 670 MHz by the amateur-satellite service is limited to the Earth-to-space direction.*

5.43 1) Where it is indicated in these Regulations that a service or stations in a service may operate in a specific frequency band subject to not causing harmful interference to another service or another station in the same service, this means also that the service which is subject to not causing harmful interference cannot claim protection from harmful interference caused by the other service or other station in the same service.

25.11 7) Administrations authorizing space stations in the amateur-satellite service shall ensure that sufficient earth command stations are established before launch to ensure that any harmful interference caused by emissions from a station in the amateur-satellite service can be terminated immediately (see No. 22.1)." (ITU, 2016).

One of the most important considerations is that amateur frequencies must not cause harmful interference. It is used on a secondary basis. The ITU will accept or reject the frequency and the IARU publishes it. The process can take up to 12 months, so it is recommended that ISU keeps in mind this timeline when following the Roadmap as shown below in Figure 5.15.

Timeline: 18 months

Step 1	Contact ANFR
Step 2	Start the procedure with ANFR and CNES Expert
Step 3	Fill the procedure with the help of CNES and IARU
Step 4	ANFR/ Amateur send the request to ITU
Step 5	Response from ITU
Step 6	Coordination with IARU for amateur frequencies and submit the coordination agreement to ITU
Step 7	ITU records and publish the frequencies in MIFR

Figure 5.15. Steps for an ISU ChipSat Mission to request amateur frequency allocation

5.4.2.2 Commercial Missions

The ISU Roadmap is oriented at launching scientific missions for educational purposes. However, in the future a portion of the ChipSats within the deployment spacecraft could be offered with cooperating universities. Additionally, ISU might decide to allow partnering institutions to use scientific data collected by the ChipSats. In this case, the procedure to request frequencies is different. As it will be considered a commercial mission if you sell data, the procedure for allocation follows the regular one for any satellite. If there are many ChipSats, the request must describe the constellations and the purpose of the satellites when filing.

The first step is to file a request through ANFR to the ITU. Then, the other administrators of satellites potentially impacted by this will have 4 months to comment on the parameters and possible interferences. ISU needs to file an Advanced Publication of Information (API) for the administration (ITU, 2016). The other operators answer through letters to ANFR who will then transmit the information to ISU. ISU will need to adjust the frequencies and the location and choose a few different frequencies for the launch. ISU will need to describe the exact frequencies and transmit this information again to the ITU (through ANFR). The process takes up to 18 months and is described in Figures 25 and 26 (Welter, 2020).

The process of requesting frequencies for a commercial satellite is described in the Code des Postes et des Communications Électroniques (CPCE) (Code des postes et des communications électroniques, 2020).

1. Mission of ANFR (Article L43)
2. Satellites Frequencies allocation (Articles L97-2 à L97-4)
3. Radioelectric Frequencies (Articles R20-44-5 à R20-44-30)
4. Satellites Frequencies (Articles R52-3-1 à R52-3-21) (CPCE)

The World Radiocommunication Conference 2019 (WRC-19) issued regulations making it easier for small satellites to register but this does not change the costs (ANFR, 2018). The costs of requesting a frequency and coordinating with other operators are usually around €20,000 (approx. $22,337 USD) (Welter, 2020). This is something that ISU will need to keep in mind when proceeding with the missions.

Even if the mission takes the form of one CubeSat hosting 200 satellites, and sharing the ride with other universities, ISU will be responsible. This also requires that the operators of the satellites prove that they can switch off their satellite. Therefore, potential commercial missions from ISU will require adequate planning and budget management as described in Figure 5.16. To supplement this, Figures 5.17 and 5.18 show steps for commercial satellites with and without coordination respectively.

Timeline: 24months

Step 1	File a request to ITU via ANFR
Step 2	Technical Coordination with potentially affected operators
Step 3	Authorization to exploit frequencies assignation requested in the ITU file
Step 4	If terrestrial exploitation is needed, authorization by ARCEP (Autorité de Régulation des Communications Électroniques et des Postes)

Figure 5.16. Authorization and steps to operate a commercial satellite in France

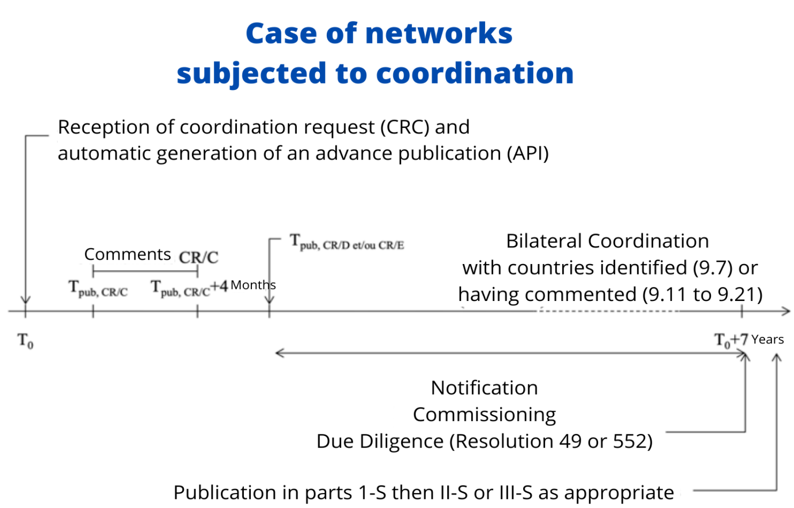

Figure 5.17. Steps for commercial satellites with coordination (Welter, 2020)

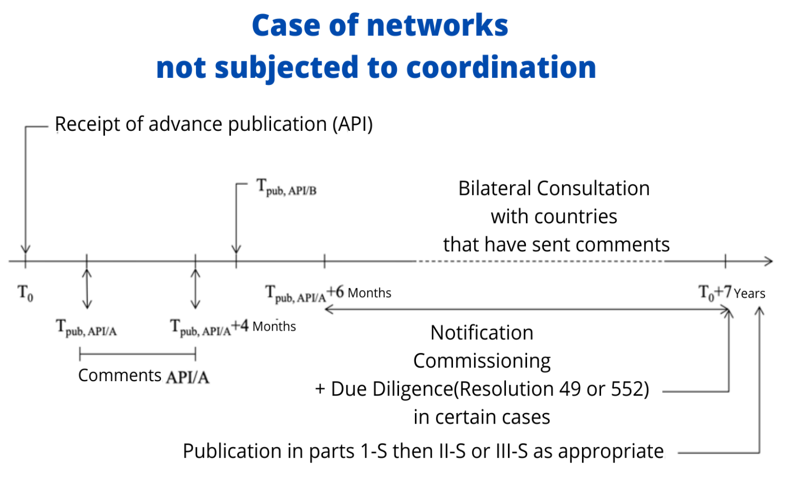

Figure 5.18. Steps for commercial satellites without coordination (Welter, 2020)

Overall, the process to request frequency allocation from the ITU is well explained, adapted recently for small satellites, and well supported by ANFR and CNES team in France. It will be long and can be costly but it is not seen as a major constraint in for ISU ChipSat Roadmap.

5.4.3 Space Debris Prevention and Mitigation

ISU ChipSats are proposed to be deployed by CubeSats which can release hundreds of ChipSats at a time. However, their small size, lightweight and large numbers have caused concern regarding space debris. The end-of-life strategy for ISU ChipSat Mission will fall within the global regulatory framework for satellite disposal and comply with the Space Debris Mitigation Standards/Handbooks and Space Debris Mitigation Guidelines promoted by The Inter-Agency Space Debris Coordination Committee (IADC). The fundamental principles of these guidelines are as follows:

1. Prevention of on-orbit breakups
2. Removal of mission terminated spacecraft from the useful orbit regions
3. Limiting the objects released during normal operations (Kato, 2001)

To avoid contributing to the accumulation of mass in orbit, the proposed space debris strategy for ISU ChipSat Mission is as follows:

1. Deploy ChipSats at altitudes below 300 kilometers to ensure the ChipSats will burn up on re-entry into the atmosphere within a matter of weeks
2. It is better to deploy ChipSats into the lowest orbit where they can avoid colliding with other spacecraft before re-entering due to atmospheric drag. This will also avoid the area between 800 – 1400 kilometer altitude which is an extremely concentrated area for spacecraft

3. Since ChipSats are gram-scale satellites with lifetimes of days to weeks, they would not be a resident space object, and the risk of collisions with other spacecraft is relatively low. So ChipSats will not be the main threat of contributing to the accumulation of mass in LEO

5.4.4 Legal Challenges Conclusions

Frequency allocation and licensing procedures will need to be started simultaneously before ISU ChipSat Mission. These are important steps necessary for the successful completion of the mission. The frequency request process takes up to 18 months, while the authorization is approximately 6 months. Questions such as international liability and export control regulations should be taken into account. The following Table 5.8 summarizes legal questions ISU ChipSats team should address when launching a potential ChipSats.

Table 5.8. Checklist of legal considerations when preparing an ISU ChipSats mission

Topic	Questions to ask	Regulations	Challenges
Registration and authorization	Which Treaties are applicable? Who will be the Launching State? Is there More than one? Who is the State of Registry? Who is registering the space object?	Article VIII OST Article III REG Article I LIAB	Length of procedures Legislation not adapted to small satellites
International & national frequency allocation	What data is sent to and from the satellite? Which frequencies are the best? Which band type? What type of frequencies licences? How to coordinate and manage the Frequencies?	ITU Constitution ITU RR and Definition ANFR Regulations WRC-19 Resolution (provision for small satellite)	Cost Amateur frequencies definition
Export control	Where are the components coming from? Which companies/suppliers? Which Countries? Are they considered military items or dual-use? Do they require a licence or end user to be exported? To which authority do you need to ask for the licence/end user?	Arrêté du 27 Juin 2012 EU Council n°428/2009 Regulations ITAR / EAR Others national export control regulations	Complicated procedures. Time constraints to draft the licence
Jurisdiction, control and liability	Which State has jurisdiction? Who is responsible? Which entity? Does the national legislation require insurance? Specific requirements	Article VI, VII, VIII OST REG French Space Operations Act 2008	Insurance fees not adapted for small satellites Legislation not adapted
End-of-Life	Is the ChipSats in accordance with Space Debris Mitigation Guidelines? Will the satellite burn-up on entry?	IADC Space Debris Mitigation Guidelines COPUOS Space Debris Mitigation Guidelines. French Space Operations Act 2008	Legislation not adapted to small satellites No control over the satellite for de-orbiting

Legend:
CPCE (France)
CMR-19: Conférence Mondiale des Radiocommunications 2019
EAR (US)
ITAR (US)
LIAB: The Convention on International Liability for Damage Caused by Space Objects of 1972
OST: Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies of 1967
REG: Convention on Registration of Objects Launched into Outer Space of 1974

5.5 Space Education and Outreach

This section addresses the second element of the proposed Roadmap aimed at reinforcing ISU as a leader in Space Education through the use of an Outreach Program and associated activities. It is proposed to use ChipSats as a cost-effective way to perform global space outreach.

5.5.1 ISU ChipSats Outreach Program

Inspired by the capabilities of ChipSats, there is a vision to leverage ChipSats for ISU to lead a global outreach campaign. Promoting inclusiveness and providing a space education that is clear, engaging, and fun to those who may not have access to technology and knowledge is key to success. The purpose of ISU Outreach Program is to educate young people while working towards ISU Institutional Objectives.

The campaign targets high school and university students, with a strong emphasis on female students, who are passionate about space and are seeking to learn about the diverse space-related disciplines. Furthermore, the campaign will aim at nations currently underrepresented in space education and the space sector with an emphasis on the countries listed in ISU Strategic Objectives: Africa, Japan, Latin America, Middle East, Russia. Shared communication between ISU and its alumni network is encouraged to ensure the campaign message is received on a global scale. Partners of interest with whom to share this message include the European GNSS Agency (GSA), Société Européenne des Satellites (SES), OHB, and Telespazio.

The Outreach Program involves the distribution of ChipSat kits which aim to educate students on satellite assembly and provide them with the opportunity to learn coding fundamentals. This campaign has a general focus on the STEM disciplines. However, this campaign intends to remain faithful to ISU's 3Is philosophy and there will be opportunities for inclusion from alternative disciplines. The kit will contain ISU-developed and leadership-accredited training materials. The desired outcome of this campaign would culminate in the organization of a student competition where they can apply learned knowledge on satellite applications. As a final step, an ISU-organized symposium on AttoSat applications for enhancing our understanding of space science and providing insight into the ethical considerations on the use of space. Commencement of the outreach campaign is targeted at early 2021 lasting up to a year. Successful campaign execution and expressed continued interest from participants and other parties may subsequently lead to an annual campaign occurrence.

The following major steps illustrated in Figure 5.19 below must be taken to ensure the outreach campaign is successfully executed:

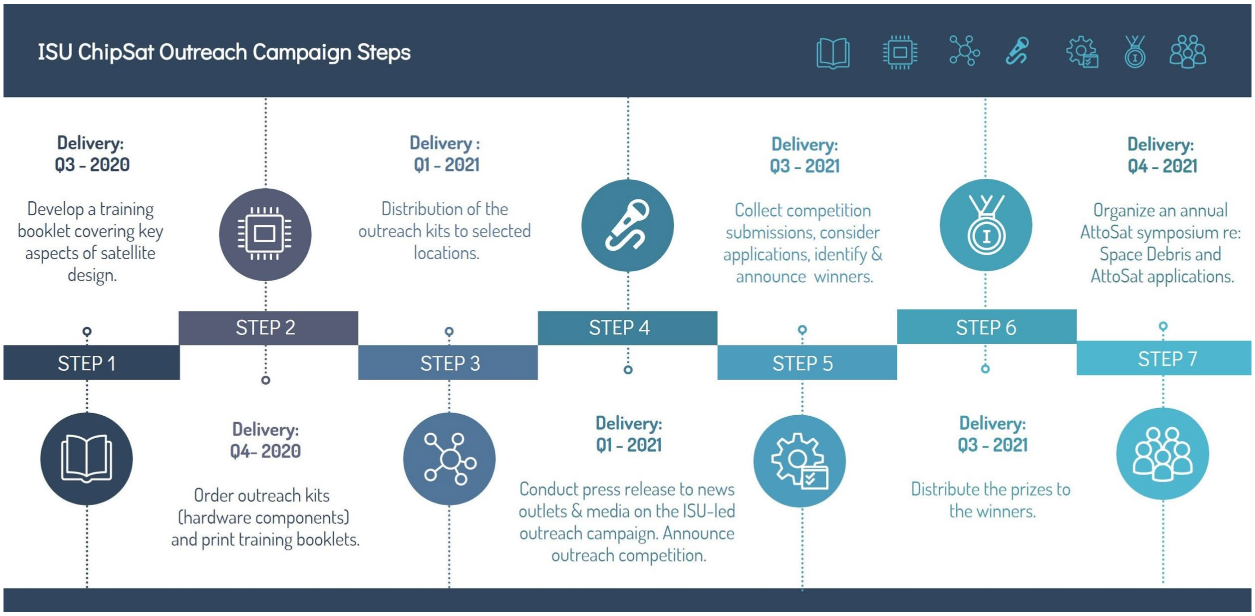

Figure 5.19. Outreach Campaign Summary

5.5.2 Outreach Program Benefits

ISU's Board of Trustees schedules an annual review of ISU's Strategic Plan as well as its respective Execution Plan (International Space University, 2020). The last version of the Strategic Plan defined, based on SWOT analysis, the following Institutional Objectives:

1. Enhance the quality, recognition, and range of programs and research
2. Increase ISU enrollment while enhancing the quality and diversity of the student and participant body
3. Reinforce financial stability and ensure growth for the University
4. Promote ISU as the best source of interdisciplinary, international intercultural space education.
5. Take full advantage of key assets including ISU staff, alumni, faculty, partner organizations, and the ISU Central Campus facilities in Strasbourg

The Strategic Plan outlines the action plans for each objective. These indicate resources, objectives, timescales, deadlines, budgets, and performance targets for each goal. The proposed Outreach Program should be considered an element of some of these action plans. The Outreach Program will address the Objectives as described in Table 5.9.

The proposed Outreach Program offers several potential benefits that align with ISU's current strategies on reinforcing the institution's strengths, to cover areas of improvement, pursue opportunities, and counter threats. Table 5.9 summarizes this.

Table 5.9. ISU Outreach Objectives

<table>
<tr><th>Benefit</th><th>Proposed Actions</th></tr>
<tr><td colspan="2">Objective One</td></tr>
<tr><td>Funding opportunity for ISU Space Payload Laboratory</td><td>An annual symposium will provide an open invitation to interested parties who may wish to participate in the Outreach Program by offering sponsorship</td></tr>
<tr><td colspan="2">Objective Two</td></tr>
<tr><td>Improve integration and brand recognition among mainstream academic networks and expand ISU’s influence, reputation around the globe via collaborations with distinguished universities</td><td rowspan="3">Students worldwide are brought together through competition participation in partnership with other universities. This competition will attract top students who may not know of ISU. Similarly, proposals such as the addition of a new space education program aimed at university students in a workshop-type format relating to ChipSats will boost ISU recognition</td></tr>
<tr><td>Improve integration and brand recognition among universities that do not have a space curriculum</td></tr>
<tr><td>Develop a network of “feeding” colleges or universities to ensure a more regular flow of applications, and a process of attracting top candidates</td></tr>
<tr><td>Increase the female/male ratio of the students. In all programs, to achieve a 50/50 balance</td><td>The proposed competition theme will specifically target this</td></tr>
<tr><td>Increase the student enrollment from currently under-represented geographic regions (Africa, Japan, Latin America, Middle East, Russia)</td><td>The competition may represent an easy way to access regions where, otherwise, ISU has no presence. The mentioned regions can become the focus of the Outreach Program</td></tr>
<tr><td colspan="2">Objective Three:</td></tr>
<tr><td>Reinforce financial stability and ensure growth for the University</td><td>The Outreach Program will bring publicity and media attention to the University. Also, reaching out to high school students will promote ISU as a proactive space education leader and will ensure stability of student applications in future year</td></tr>
<tr><td colspan="2">Objective Four</td></tr>
</table>

Ensure effective worldwide public relations and promotion of ISU	Press release to media about the Outreach Program and competition announcement. Media lists will include space publications and education publications
Objective Five	
Build local academic networks in and near Strasbourg, including in neighboring countries, to enhance education reach and research partnerships and reinforce Local Outreach activities	Outreach campaigns will initially target Strasbourg, France and other neighboring countries. The campaigns can target both universities and primary and secondary schools with personalized kits for each
Act a valuable catalyst for the local and worldwide communities engaged with space activities and promote the Central Campus as a venue for international meetings	The symposium could be a start of more events held at ISU that bring together ISU alumni, academia, government agents, industry, and others

5.5.3 Outreach Program Metrics

To measure the benefits associated with the proposed Outreach Program a series of metrics are required. Following the philosophy of a lean company start-up approach, only actionable metrics will be used. Statistics must link to specific tasks that are easy to measure, comparable, and shows improvement or worsening directly tied to the Institutional Objectives. These shall not only be actionable but also accessible and auditable. In that sense, the database must be accessible to all personnel involved in the Outreach Program but should be owned by a single person. The metrics shall be obtained following cohort analysis where possible and not cumulative metrics. The retention rate, churn rate, and rate for the previous metrics should be computed.

ChipSat Symposium

1. Number of attendees
2. Number of ISU alumni
   i. Country of origin
   ii. Professional status
3. Number of non-ISU attendees present
   i. Country of origin
   ii. Professional status
4. Number of research papers submitted for the symposium from non-ISU attendees
5. Number of requests to hold similar events at ISU

Outreach Kits and Competition

1. The number of institutions in which kits were delivered
2. Number of underrepresented countries and institutions in those countries to which kits were delivered
3. Number of members from institutions where kits were delivered that applied to ISU in the following 12 months compared to previous years
4. Number of people who participated in the competition and applied to ISU in the following 12 months compared to previous years
5. Media engagement - number of articles published

Online Campaign Metrics

1. Engagement numbers with social media posts pertaining to the campaign, i.e. reach, shares, increases in audience size during campaign
2. Number of page visitors to dedicated ISU website
3. Number of visitors navigating other non-outreach ISU website pages
4. Number of email newsletters registered for dedicated campaign information dissemination

General

1. Number of people who apply to ISU programs and get to know about the university due to the Outreach Program
2. The number of new relationships/partnerships developed through the Outreach Program
3. Number of funding secured for Outreach Program

5.5.4. Training Materials and ISU ChipSat Kit

5.5.4.1 Kit Purpose & Training Booklet

This training kit is developed for school and university students with no or little previous experience in electronics. It is designed for a better understanding of the working mechanism of a satellite without any prior knowledge and expertise in this field. The assumed working group required to assemble a single training kit is three to four students.

This training kit would provide a cost-effective, comprehensive experience of preparing a ChipSat with a simple design mechanism. After integration, simple ground testing will follow to determine the capability of different components. This will be discussed further later in the chapter.

The expected learning outcomes for the students are proposed:

1. Understand the importance of satellites in daily life and their variety of applications
2. Develop the knowledge on basic components of a satellite, how to build it and how to make it operational
3. To extend the knowledge of Physics from theoretical to practical behind satellite orbiting

4. Develop an understanding of the manufacturing of simple electronics circuit boards
5. Develop an understanding of the function of different components of an electronic circuit board like sensors, microcontrollers, capacitance, resistance, diodes, etc.
6. Provide a hands-on training capability among students and teachers
7. Be a trigger to new ideas, experiments, and exploration
8. Aid in developing a basic understanding of a computer programming language (basic knowledge of C/ C++, Arduino) which are available online at free of cost
9. To understand the concept of space debris and the probable hazards caused by this
10. Understanding the registration and licensing issue of any space object meant to fly. So this kit would provide the specifications with the requirements to build and ground testing only, not covering the launch
11. To extend student's knowledge, understanding and expertise to organize a competition and the benefits of organizing it (Explanation of a competition)
12. Be a good team-building activity

The kits will be distributed to the outreach sites in 2021. The chosen outreach sites will be based on the geographically under-represented areas that ISU anticipates has potential in attracting new students; predominantly Latin America, Africa, and Asia. The outreach sites will be those already partnered with the United Nations.

Using this outreach kit, ISU can provide training programs but also recognize the emerging talents amongst students by organizing competitions, and hackathons in the future. The use of this kit is not restricted to knowledge development and it is a great hands-on and team-building opportunity also among ISU students.

The Outreach Program will help to strengthen the bond between ISU and its current sponsors and partners. The further sections explain the methodology and costs of the ChipSat kit and explore opportunities for funding.

5.5.4.2 Outreach Kit Components

The outreach kit is designed for both high school and university students. The kits are intended to provide students with experience in ground operations/testing and are not expected to be launched to space. To design the basic ChipSat for outreach training purposes, widely available COTS components were chosen. The component and the cost breakdown is proposed in Table 5.10.

Detailed research was conducted to select the best solution for the ChipSat base. The custom-designed PCB with a soldered ATmega328 microcontroller is currently the best option for ChipSat base. This option will allow the users to experience building a ChipSat by imitating the low mass and small size. The proposed outreach kit will enable participants to gain experience of working with small satellites and a chance to learn the underlying principles through hands-on training. The learning outcomes can also be tailored based on the skills desired to be acquired during the workshop. The sensor of choice can be selected by the outreach site or a sponsor based on the educational value and the price. The ChipSat will be able to communicate with the students' laptops using the selected 2.4 GHz transceiver. This solution will demonstrate the communication ability of the system and will transmit the measurements from the sensor to the computer. It will provide a learning opportunity for programming basics.

Further study was conducted to assess the basic components for the outreach kit and their cost. The learning outcomes were incorporated to ensure the components fulfill their educational role. The list of the components is presented in Table 5.10.

Table 5.10. Basic components for the outreach ChipSat training kit with sensor options

Components	**Specification**	**Unit Price (USD)**	**Purpose**	**Learning Outcome**
Base plate				
PCB designed at ISU and component assembly (PCBWay, 2020)	7x7 cm	2.50	Pre-soldered components	Could learn soldering with 1 trail PCB
ATmega328 (Atmel, 2020)	Microcontroller	3.0	Brain of the ChipSat	Working with Arduino libraries
Basic components				
Transceiver (Walmart, 2020)	nRF24L01+ module 2.4 GHz worldwide ISM frequency band	2.66	Transmits and receives signals	Learning programming and satellite communication
Solar cells (TrisolX,n.d.)	TrisolX Solar Wings	4.0	Convert solar energy to electrical energy	Learning the working principles of solar cells
Gyroscope and accelerometer (Walmart, 2020)	MPU6050 -MEMS accelerometer and a MEMS gyro	4.99	Accelerometer and gyroscope in one chip Inexpensive but efficient	Learning about satellite stabilization methods
Resistors (Walmart, 2020)	Set of 300 of 17 values. Price optimized for 17	1.0	Needed to manipulate the voltage required for different components	Learning electronics and physics
Capacitors (Walmart, 2020)	Different values of capacitors. Price optimized for 10	1.0	To regulate the current and voltage in the circuit	Learning to work with different electrical components

Total:		**19.15**		
Sensor Selection (only one sensor included in one kit)				
Temperature, Humidity, Pressure and Volatile Organic Compounds (VOC) sensor (AliExpress, 2020)	BME680 Temperature, Humidity, Pressure and Gas Sensor Breakout Board Module 3.3V/5V for Arduino	10.53	Can measure temperature, humidity, pressure and also detect volatile organic compounds (VOC)	Learning to measure the VOC in the surrounding
UV sensor (AliExpress, 2020)	ML8511 UV sensor	4.41	sends an output analog voltage that is linearly related to the measured UV intensity	Learning about the optimal UV intensity for humans and level in the classroom
GPS sensor (AliExpress, 2020)	NEO-6m	9.33	Needed for Navigation Satellite Positioning	Learning to work with GNSS
Total with min. sensor price:		**23.56**	Including only GPS sensor	
Total with max. sensor price:		**29.68**	Including only VOC sensor	

Note: the value and quantity of resistors and capacitors will be calculated when the PCB design is completed, thus the corresponding price is an approximate value and may change

Once a basic satellite assembly is achieved during the workshop using the specific components the students will be able to perform the following ground tests:

1. The spacecraft can be switched on to a predefined routine operations mode. Onboard capacitors (optional) may start charging and switch on the microcontroller. Once powered up, onboard magnetometers begin working and any changes in the magnetic field will be detected. Current and voltage produced by the solar arrays could be tested on ground using a multimeter in the closed circuit under the Sun's exposure

2. Students can perform ground testing of initial radio transmission capability using an external battery supply

3. The students can measure the temperature, humidity and pressure in their classrooms and surroundings using the ChipSat. The on-board sensors will help to measure them

4. The students can also identify the existence of volatile organic compounds like Alcohols, nonvolatile inorganic compounds like Carbon Monoxide in their surroundings with the help of different kinds of sensors on-board

5. The students will be able to track the location of their satellites on ground with the help of the GPS sensor on-board

6. The students will be able to measure the intensity of UV radiation in their classrooms and surroundings using the on-board UV sensors

7. Students can determine the orientation of their spacecraft with the help of the onboard gyroscope and accelerometer

5.5.4.3 Assumed Outreach Influence

It is assumed that one outreach site has an attendance of 30 students. One ChipSat hardware is expected to engage 2 students working together. The further costs are calculated based on one box dispatched to an outreach site containing a set of learning materials and 15 individual ChipSat hardwares. Hence the influence of proposed costs is 1,500 students. This number can be increased with number of sites.

5.5.5 Outreach Program Cost

The following cost breakdown, shown in Table 5.11 below, represents a top-level estimation of the total campaign costs based on the campaign steps outlined in Section 5.2.1. It is assumed that the average ISU administrative employee hourly rate is $50, faculty rate is $80 and the President's rate is $100 per hour. The Outreach Program is assumed to consume approximately 1.5 days a week of administrative effort and the initial effort of 50 hours from ISU leadership to develop training materials.

Table 5.11. Proposed cost breakdown for the outreach campaign

	Task Description	**Effort Required**	**Cost (USD)**
1.	**Training Materials & Kit Development**		
	Training kit hardware design approval based on TP input	Bulk order of the components for $29.68 each (max. price). 1,000 pieces order	$29,680
	Training booklet development	50h of labor ISU staff + 5h review time and approval	$4,400
2.	**Outreach Kits (Suppliers)**		
	Components bulk order	Administrative effort: 4 hours total	$200
	Training booklet printing	Administrative effort: 5 hours total	$250
	ISU Administration	10h of labor in total for ordering components and delivery receipt	500
3.	**Campaign Logistics and Management**		

3.1.	Distribution costs A4 weighs about 5 g, assume, each booklet is 20 pages long and ChipSat Kit 20 g, that gives 120 g per kit	Assumed shipment weight is 10 kg with DHL to Japan/South Africa/Bolivia in a box of 50vmx40cmx20cm is $240 each. 1 box containing 20 kits with teaching materials	$12,000 .
3.2	Campaign management tasks	Assumed 3 hours per week to answer queries. Duration 5 months	$3,000
3.3.	Communication with the outreach sites	Assumed 5 hours per week to receive feedback and answer queries	$5,000
4.	**Publicity and Media Relations**		
	Communication with the media (press release, announce the competition)	Effort: 3 hours per week, alternating workload	$3,000
5.	**Competition Management**		
	Collect competition Submissions	Assumed 20 hours of administrative effort	$1,000
	Announce the winners	3 hours of ISU President effort and 10 hours of administrative effort to communicate with the winners	$800
	Distribute the prizes to the winners	30 hours of administrative effort in total	$1,500
	TOTAL:		**$61,330**

5.5.6 Outreach Program Funding Sources

Authors of this outreach proposal reached out to the industry leaders to consult the idea and gauge their level of interest. Primary satellite industry companies currently supporting ISU expressed positive feedback towards the campaign and are ready to cooperate in order to reach out to females and students from the underrepresented regions of the world. Consulted organizations include SES, OHB, Telespazio, and the GSA. All of the organizations expressed an interest in participating in the Outreach Program by sponsoring the activities related to purchasing the hardware and logistics. All of the organisations see the benefit for their own strategic goals. Initial conversations revealed SES is prepared to take a lead sponsorship role for the campaign with GSA expressing willingness to provide UN access to outreach sites as part of their own campaign. Hence, it is strongly recommended ISU leverage the groundwork established and continue generating momentum by driving the outreach campaign forward.

Organizations arranging similar outreach programs were consulted to understand the logistics behind such a campaign and to establish cooperation in the area of educational exchange. Consulted organizations and companies include University Space Engineering Consortium (UNISEC) and OPEN-Cosmos. Both organizations are well established and have a successful track record in delivering training for electronic hardware.

Open-Cosmos has developed its own software called BeeApp to develop space missions. The software is available free of charge for schools and universities to develop their own space missions and also it provides a platform for programming interface with the satellite hardware. Open-Cosmos has already established cooperation with ISU in delivering satellite workshops for MSS and Space Studies Program (SSP) students.

5.5.7 AmbaSat Trial Launch

The ChipSat Team identified AmbaSat, a kickstarter which offers an affordable ChipSat kit and launch to LEO. It is the only opportunity to launch a ChipSat available on the market at the time of writing this report. The purpose of AmbaSat is also to introduce interested people at ISU to basic satellite technologies. The ChipSat Team decided to use the project budget to purchase the kit to gain knowledge and experience on ChipSat build and logistics of the launch process. This opportunity is a great start to familiarise ISU students with the ChipSat hardware and offers tremendous potential for ISU educators to trial the outreach. Once in orbit, the satellite can be used for outreach purposes to attract media attention to the ChipSat technology.

5.5.7.1 AmbaSat Concept

AmbaSat is an AttoSat that is 35 millimeters in length on each side and has a thickness of 2 millimeters. Incorporated in the kit are structural based solar cells and coding support. It can also transmit data to more than 5,000 Earth-based The Things Network (TTN) receivers without the need for professional radio receiving equipment. The kits will be shipped by the organizers to the customers between March and April 2020 and the launch is expected in 2021. Therefore, the assembly of the ChipSat will be executed in ISU before this report is published.

There are two options to purchase AmbaSat kits. The first is a non-flying kit used only for assembly and testing. This kit is shown in Figure 5.20 and costs €68, or $77. A second kit includes a supplementary transmitter and solar panels for €250, or $284, and includes the launch to LEO on a NEPTUNE rocket with the Interorbital launch company.

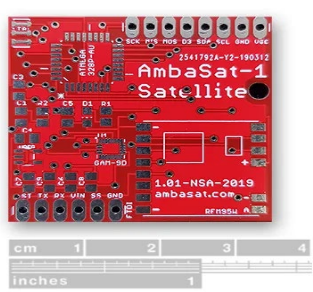

Figure 5.20. AmbaSat satellite kit (AmbaSat, n.d.)

5.5.7.2 AmbaSat Potential and Timescales

The hardware designs for AmbaSat-1 are open source and simple to navigate. The required components are readily available and AmbaSat-1 has been designed with an innovative communication setup. AmbaSat did not develop a ground station for satellite operational support. Instead, LoRaWAN technology and TTN were leveraged to facilitate ground station services. TTN has traditionally been used for remote sensing tasks. LoRaWAN radios enable off-grid devices to send data packets to ground stations of low power. As shown in Figure 5.21, TTN has many gateways integrated into its wider system providing broad coverage across wide areas (Wulff, 2019). Overall, Ambasat is available for purchase, assembly, and launch to everyone.

Figure 5.21. TTN gateway map (The Things Network, n.d.)

The timeline for the AmbaSat project is summarized below:

1. Estimated hardware assembly time: approximately 4 hours
2. Estimated software development time: approximately 2 hours
3. Two months before launch, it will need to be returned to the laboratory for pre-launch testing. Through a two-week soak-test, it can be ensured that AmbaSat can fly in space for a long time. Finally, a vibration test is performed. All testing time is about one month
4. Proposed Launch Date: 2021

5.5.7.3 AmbaSat Legal Challenges

AmbaSense, the owner of the AmbaSat Kickstarter will handle the legal requirements as the AmbaSat remains their property. ISU students will simply assemble and develop the software before sending the AmbaSat back. They will therefore be the main point of contact to apply for authorization and licences, and will remain liable for the AmbaSat. Space debris is not a concern since the satellites will re-enter after a period of maximum three months due to the predicted orbital decay (AmbaSat, 2020).

5.5.8 Space Education Conclusion

Space education is a high-priority strategic goal for ISU. This goal can be realized using ChipSats; a cost-effective, easy-to-make satellite with readily available electronic components. A ChipSat can be assembled without complicated hardware, software, significant prior training, sophisticated testing, and advanced laboratory facilities. This versatility opens up an opportunity to provide space education to both teachers and students alike by exposing them to basic integration and installation techniques for ChipSat components. Students will have the opportunity to develop their own satellite while enriching their knowledge through training on programming and electronics circuit design.

5.6 Project Management for ISU Roadmap

The deliverables mentioned in the above sections propose a series of steps to be implemented by ISU. Successful delivery of these steps will require an organizational framework to be in place. This section presents a proposal for organization and management and an estimated effort to deliver the Roadmap. The Roadmap also, addresses ISU Institutional Objectives Four and Five aimed at staff development and ISU being attractive for its source of interdisciplinary Space Education. Moreover, the ChipSat Team suggests strengthening the bond with ISU partners by inviting them to share their expertise.

5.6.1 Timeline of Key Activities

The proposed ISU Roadmap contains three main streams of activities: ISU ChipSat Program, Regulatory Framework and Outreach Program. The relevant activities for each have been discussed in detail within their respective sections. A summary of the key activities is displayed on the timeline in Figure 5.22.

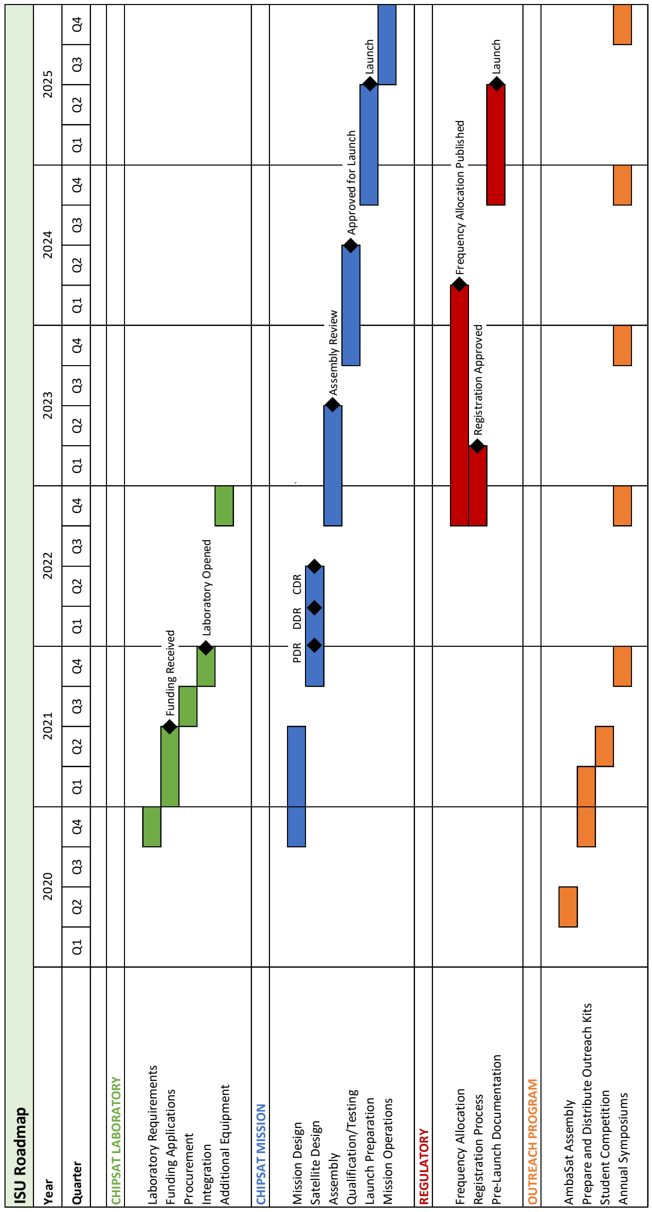

Figure 5.22. ISU Roadmap Activity Timeline

5.6.2 Recommended Organizational Structure

The recommended management strategy for ISU ChipSat activities is detailed by the following:

1. As the owner and leader of its own ChipSats technology, it is recommended ISU personnel will manage and lead this program within the existing Space Payload Laboratory structure
2. It is assumed that a large portion of the work will be done by ISU students, who will gain experience and knowledge at the topics they are being engaged with. In addition, students who work on these projects should be offered the opportunity to stay involved in the ISU ChipSat Program as contributors or consultants even after they graduate

3. It is recommended to establish a steering committee for ISU ChipSat activities, which will guide, review and approve the annual plans. Members of this committee will include:

1. ISU staff, leading the following activities:
    i. Program management
    ii. Budget allocation
    iii. Procurement
    iv. Develop teaching curriculum and materials
    v. Maintain knowledge and documentation
2. ISU alumni (preferably those with experience in ISU ChipSat Program):
    i. Support with knowledge and insights
    ii. Support with outreach activities
3. Representatives from the space industry and agencies, who will reasonably provide:
    i. Valuable market and technology insights
    ii. Scientific and business guidances and priorities
    iii. Access to technical expertise whenever needed
    iv. Access to test equipment/facilities

Considering the above points, the organization chart in Figure 5.23 below shows the suggested structure for arranging personnel to ensure the activities are managed in the most effective manner.

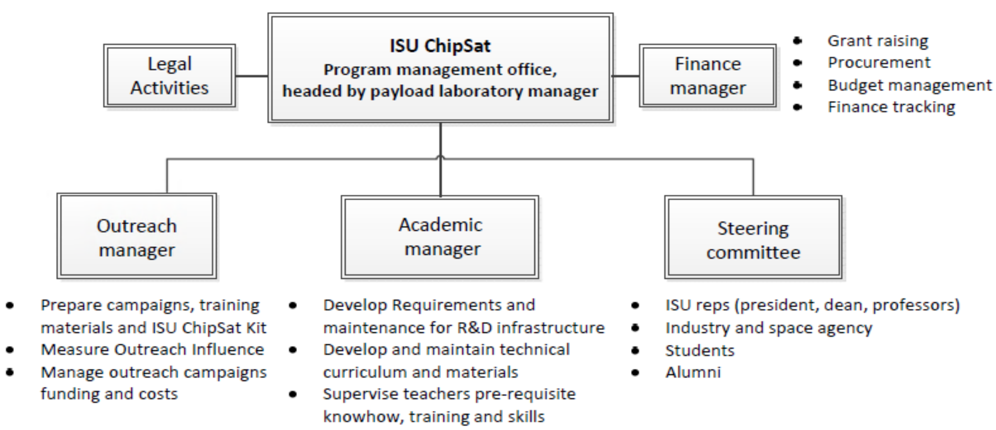

Figure 5.23. Recommended Organization Chart

5.6.3 Staff Effort Required

Based on the task breakdown included in each element of the Roadmap, the total staff effort was identified and presented in Table 5.12. This estimation informs a decision whether to spread the workload across the current staff or to hire additional personnel of a desired skill set.

Table 5.12. Estimated Staff effort required to deliver ChipSat Program

Category	Skillset	Effort (hrs/week)
ChipSat Program	Senior Management	3

	Project Management	15
	Academic Manager	35
Outreach Program	Admin	12
	Senior Management	1
Regulatory Framework	Project Management	20
Finance Management	Finance Manager	15

Based on the above estimation is it recommended to invest in full time employment of one Project Manager professional and one Academic Manager (PhD level). The benefit of investment is to establish a coordinated ISU ChipSat Program and apply for grants and funding for future research.

5.6.4 Staff Development Opportunities

The ISU staff will be an important asset in delivering the ISU ChipSat Program. Hence, establishing the Program creates an opportunity to apply for funding and grants to offer staff training and research to broaden the knowledge listed in Institutional Objective Three. Training the staff members will result in creating the knowledge base at ISU and to lower the attrition rate. It will create an attractive workplace for “high-quality pool of applicants to ISU programs” (International Space University, 2019).

5.6.5 Cooperation with Industry and Alumni

The proposed Roadmap is designed to offer many opportunities for ISU to cooperate with industry and alumni. The summary of ideas proposed throughout the Roadmap that are relevant to industry and alumni cooperation are:

1. Invite alumni and industry to the advisory board of ChipSat Program
2. Establish or strengthen the cooperation with other universities in exchange for students and facilities to deliver high-quality education
3. Involve industry to participate in the Outreach Program and attend AttoSatellite Symposia
4. Invite industry partners to sponsor Individual Projects to contribute to ChipSat technology development
5. Develop ChipSat knowledge exchange hub
6. Develop a long-lasting relationship with CNES to support the frequency allocation framework

5.7 Roadmap Cost Summary

This section provides a cost estimation for the overall ISU Roadmap activities. ISU will first need to invest in the AmbaSat kit for exposing the students and the supporting faculty to the ChipSat components and their integration before starting their ChipSat campaign and building their own ChipSat. The cost of the

Ambasat-1 kit includes the integration in the KickSat CubeSat, pre-launch testing and launch in LEO orbit using launch vehicle NEPTUNE in 2021.

For the Outreach Program, it is highly recommended for ISU to hire an expert dedicated to this program or take into account the extra labour hours of ISU staff. For this, the cost of training materials & kit development with the cost of a single outreach kit has been estimated including activities like the manual development, publicity, outreach campaign and competition management etc.

For building their own ChipSats, ISU will need a dedicated laboratory facility. The cost of preparing the ISU ChipSat Laboratory with the recommended equipment, excluding the already available equipment in the Make-It-Space and ISU Payload Laboratory, has been approximately estimated. The cost of the ISU ChipSat Mission is estimated using KickSat Sprites as a reference, assuming an extra cost for integration and testing (Manchester, 2013). The total cost to proceed with the Roadmap is approximately $303,030 including a CubeSat deployment platform for the ISU ChipSat Mission. The following Table 5.13 represents a top-level cost summarization of the total cost of the Roadmap activities until the fourth year in 2024, excluding the launch cost for the ISU ChipSat Mission

Table 5.13. Cost summarization of the Roadmap tasks till year 2024

Task	Cost (USD)
AmbaSat Kit	$285 - includes the launch to LEO
Space Education and Outreach Program	$61,330 (including an estimated price of $29.68 for each training kit and assuming 1,000 pieces ordered)
ISU ChipSat Hardware and Testing	$460 ($300 for components + $160 for integration and testing)
Deployment CubeSat (3U platform, external purchase)	$175,955 (including testing) (Endurosat, n.d)
ChipSat Laboratory Equipment/Tools (Purchase and Outsourcing)	$40,000
Regulatory Framework	$20,000-$25,000
TOTAL	**~$303,030**

5.8 Risk Analysis

The major risks that are associated with the execution of the proposed ISU ChipSat Roadmap were considered and are outlined below. Following ESA's Scientific Directorate Risk Management guidelines, the risks are ranked according to their risk level based on likelihood and consequence within a risk matrix, as in Figure 5.24 (Schroeter, 2001). Mitigation and avoidance techniques are identified, as seen in Table

5.14, for the risks whose rating surpasses the acceptable risk index threshold of 3C and ranked in an updated risk matrix in Figure 5.25.

R1 - Knowledge transfer

Difficult to ensure appropriate transfer of knowledge from one generation of students to the next over five years.

R2 - Deployment method

Unable to find or develop a suitable deployment method for the ISU ChipSat Mission. At the moment deployment is done via CubeSat but they are expensive and time-consuming to develop and outsourcing deployment is not currently an option.

R3 - Outsourcing of AIT facilities

AIT facilities that are not financially or physically possible to have at ISU will need to be outsourced. Finding such facilities may prove to be difficult due to location or cost.

R4 - Ineffective ChipSat development via IPs

Hardware and software development for the ISU ChipSats will rely on student IPs. It is difficult to ensure IP quality is met to an acceptable standard and there may be a lack of interest from staff and students for ChipSat related IP topics.

R5 - Excessive costs

Costs are too high to be covered by any sponsors or donors.

R6 - Liability insurance

Third-person liability insurance is required to obtain a license from France to launch a satellite. For the moment, small satellites are not distinguished from bigger ones.

R7 - License application rejection

Not able to obtain a license to launch from the French national authorities due to concerns over the ability to communicate with the ISU ChipSat or over creating space debris.

R8 - Not enough interest from outreach beneficiaries

Not enough interest expressed by schools and/or universities on receiving the outreach kits or participating in the competition.

R9 - Outreach does not result in outlined benefits

Participation in outreach does not translate into more and better applications for ISU programs, or more interest from minority groups, or better relations with other academic institutions or better promotion for ISU.

R10 - Disagreements with outreach partners

Potential partners not convinced by plan and/or want to take a path that does not align with ISU's vision and/or Institutional Objectives.

R11 - Lack of quality control

ISU is not an engineering company and has little experience sending payloads to space. This increases the likelihood of human errors that provoke overruns on cost and schedule or even the failure of the mission.

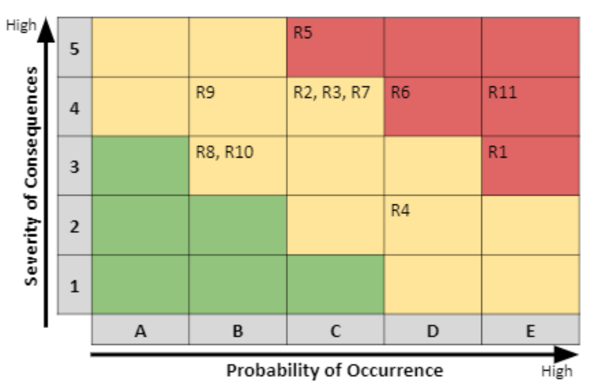

Figure 5.24. ISU Roadmap mission risk matrix displaying levels of various risks before mitigation

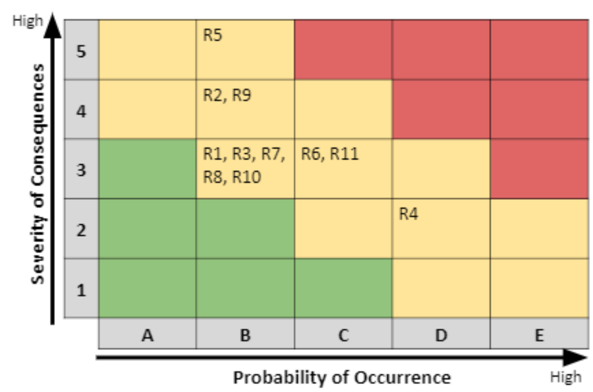

Figure 5.25. ISU Roadmap mission risk matrix displaying levels of various risks after mitigation

Table 5.14. ISU Roadmap execution risk mitigation strategies

Risk	Control Measures
R1	Establish mentorship opportunities between current and previous student cohorts Enlist past students as external IP advisors for current students interested in ChipSat IPs
R2	1. Outsource the entire development of the CubeSat for ChipSat deployment purposes 2. Establish a partnership with existing ChipSat projects, such as Ambasat, to utilize their CubeSat for the deployment of ISU ChipSats
R3	Utilize current ISU partnerships with research institutions and universities to receive assistance with identifying and utilizing their AIT facilities
R4	Acceptable risk
R5	The benefits of sponsoring ISU's ChipSat program should be made very clear The Outreach Program should be used as a funding campaign too and the outlined metrics on Section 5.5.3 should be used to convince potential donors and sponsors
R6	Most space-faring nations, including France, are holding discussions on changing the regulations regarding third-person liability and adapting them to smaller satellites. Therefore, it is expected that insurance cost drops by the time it is required for the mission
R7	The most experienced people on space design should be allocated to the communications subsystem Thought should be put into what are currently the available ways of tracking satellites of the size of a

	ChipSat. If there is a way to involve people who have previously obtained such license this should be pursued A license application should be put forward with sufficient time to allow for a second application to be submitted in case the first application is rejected
R8	Acceptable risk
R9	Acceptable risk
R10	Acceptable risk
R11	Establish a quality control manager who defines some basic guidelines on how which processes to follow and ensures different steps in development finish with internal reviews Similarly, a laboratory manager should be also assigned

5.9 Building Future Capability

The proposed Roadmap contains all the steps necessary for ISU to launch their own ChipSat within a five-year timeframe. It is important to build the capacity needed to ensure ISU can continue to lead the technology development and push the boundaries of ChipSats after the initial mission.

As such, there are several topics of interest that are suitable for students to work on, either as individual projects or team assignments, during the ISU MSS program.

5.9.1 Proposed Individual Projects

Piggybacked asteroid-flyby mission to study its properties for finding potential candidates for future mining missions

Asteroid mining is anticipated to revolutionize our future economy. Asteroids have been found to contain numerous rare Earth metals such as iron, nickel, etc which may enable cheaper construction projects in space if successfully harvested. Given the logistical challenges involved and the considerable financial investment required to establish asteroid mining operations, mission designers must be informed on which asteroids are worthy of prospecting. The deployment of ChipSats from larger satellite platforms embarking on interstellar or interplanetary missions as secondary payloads may offer insight to passing asteroids. Characteristics of interest include asteroid elemental composition and properties. This individual project seeks to address this concept by proposing a mission architecture, the required subsystems accompanied by a structural concept, suggested payloads for asteroid characterization, a piggyback strategy, deployment strategies, and an orbit analysis.

Review the feasibility of ChipSats integrated solar sail design for a mission to Mars

A key challenge for ChipSats is attitude and orbit control. ChipSats, due to their high surface area to mass ratio and rigidity, avoid the challenges large scale spacecraft sails need to overcome, such as the problem of unfolding after deployment using complex mechanisms. Taking inspiration from Project Glowworm and Alpha sail Cornell University, review the feasibility of ChipSats integrated with solar sails for propellant-less trajectory control for a mission to Mars.

ChipSat for health monitoring of currently in-orbit satellites

The small size and low mass of ChipSats enable them to be attached to larger spacecraft or orbit around it to perform health monitoring. Design a mission for the same with suggested payloads and analyse the risks associated with it.

Design and cost of an ISU ChipSat Outreach campaign

The development of an ISU ChipSat project centered around outreach must take into consideration several factors in terms of differentiation and promotion. Students should build a solid marketing plan based on the 4 Ps of Marketing and Porter's 5 Forces Model to understand external pressures and competitive advantage when vying for the attention of an identified audience. Furthermore, students should also analyze funding sources and resources needed including HR requirements both internally and externally. A coherent timeline of activities should be presented, outlining who, what, why, where, and when priorities will occur, and what is required as a measure of success.

Lunar space debris mitigation approaches

There are potential applications for ChipSats to be used in lunar orbit. Due to the lack of a lunar atmosphere, these ChipSats will not burn up on re-entry and will "litter" the surface of the Moon. Explore the options for mitigating this space debris problem including, but not limited to, in-orbit removal and surface removal. Compare these engineering solutions to a potential legal framework that may allow a certain amount of "litter" for a cost (similar to a carbon tax scheme).

Cybersecurity

ChipSat technology has not fully matured and many additional security considerations have not yet been addressed. Satellites have been hacked in the past, yet cybersecurity often does not currently receive the attention it needs. ChipSats must also have cybersecurity to protect against hackers. There are no cybersecurity standards for satellites, and new ChipSats missions do not have a precedent to follow. Examine the vulnerability of ChipSats to hackers, the potential consequences and propose solutions, drawing on the strategies used for CubeSats.

5.9.2 Proposed MSS Assignment Topics

Lunar exploration using ChipSats

The Lunar south pole is a convincing spot for future lunar exploration missions. Past missions spotted evidence of water ice, methane and more hydrogen percentage at the South pole. Design of a ChipSat deployment mechanism from a 3U CubeSat for lunar South pole at an orbit of approximately 40 kilometers for a remote sensing mission and select and justify a suitable payload sensor for your mission.

Space debris mitigation for ChipSats

The redundant, low mass and low-cost nature of ChipSats enables the launch of ChipSats as secondary payloads with ease. However, this naturally presents a debris mitigation challenge and increases the risk of damaging other orbiting satellites which could propagate the more serious Kessler effect. Investigate this issue by considering the engineering and legal aspects and advise suitable end-of-life and debris mitigation strategies.

5.10 Roadmap Conclusion

The three key elements of the ISU ChipSat Roadmap will help ISU meet the Institutional Objectives set out in the ISU Strategic Plan. The proposed ISU ChipSat Program will position ISU at the forefront of the ChipSat development and will help increase the number of missions managed within the ISU Space Payload Laboratory. Moreover, it will enhance the curriculum and student involvement within ISU's existing educational programs, such as the MSS and SSP. The proposed Outreach Program will draw positive attention and publicity to both ISU and sponsoring partners, and encourage more students to attend ISU. The purchase and launch of an Ambasat will help ISU students gain the practical knowledge of assembling and programming a ChipSat so they have the necessary skills to contribute to the ISU ChipSat Program. The regulatory framework is also important to understand so the legal challenges are considered with the ISU ChipSat Mission in particular.

The chapter has also outlined the management structure proposed to enact the proposed ISU ChipSat Roadmap. A cost summary and risk analysis have also been prepared so ISU understands the commitment and risk it will take if the proposed ISU ChipSat Roadmap is adopted. Future capability development has also been considered to ensure the knowledge within ISU grows beyond the initial ISU ChipSat Mission.

6. Future Mission Case Studies

This chapter provides further detail, including the engineering, commercial and legal aspects, of the two ChipSat missions selected during the process described in Chapter 4. Both of these missions are considered to have commercial and scientific value that can be realised in the next five to 10 years.

6.1 Space Weather Mission

6.1.1 Introduction

Space weather is defined as the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere caused by the Sun's activities and associated solar wind. It can influence both space-borne and ground-based technological systems and can be hazardous to life on, or orbiting around, the Earth.

Space weather forecasts predict solar events that can cause disruptions to important systems, such as navigation and communication, or endanger human lives. A geomagnetic storm refers to the disturbance of the Earth's magnetosphere caused by a change in solar wind, typically associated with a solar coronal mass ejection (Nowakowski, 2016). The proposed mission will be focusing on collecting data about such storms.

The proposed mission concept involves hundreds of ChipSats in LEO providing in-situ magnetic field measurements. Such a large amount of dispersed magnetometer data points collected during geomagnetic storms can be combined with measurements from elsewhere in the heliosphere and on the ground to calibrate space weather forecasting models. The data will also have significant scientific value as it can be used for heliophysics research and understanding how solar events affect the Earth's magnetic field.

6.1.2 Mission Justification

A LEO ChipSat constellation can provide high spatially distributed data regarding geomagnetic storms caused by space weather. This data can be combined with solar and ground-based measurements from other sources to help improve our understanding of space weather effects on the Earth's magnetic field. This information is important because changes in the magnetic field can lead to natural effects within our biosphere, and can also cause disruptions to technology-based infrastructure, such as satellite communication and electricity networks. While studying space weather is interesting from a scientific point of view, it also has significant commercial value in terms of the ability to predict and mitigate against the impact of space weather events.

6.1.2.1 Scientific Value

Magnetic field data from LEO with high spatial distribution will enable further studies related to space weather, the Earth's magnetic field, and other related phenomena. Examples of research areas where the new magnetic field data from ChipSats could be used is documented below.

Heliophysics

Heliophysics refers to the study of the Sun, including how the space weather it creates affects the Earth and the rest of the solar system. Spacecraft have collected data from across the heliosphere, including the Parker Solar Probe close to the Sun, satellites around Earth, and the Voyager probe at the edge of the solar system (NASA, 2020). ChipSats are not capable of solar missions, but data collected around the Earth is still an important part of understanding our Sun and space weather.

Aurora

Auroras are a spectacular natural phenomenon, visible at high latitudes, caused by the interaction between the solar wind and Earth's magnetic field. Studying auroras from the ground can help scientists understand the magnetosphere as there are limited satellites within the magnetosphere itself. Recently, a new type of spiraling aurora was observed on all-sky cameras located in Norway, and luckily, one of NASA's spacecraft was overhead to detect the corresponding compression in the magnetic field (Tran, 2019). Additional instruments in orbit such as ChipSats will increase the likelihood of detecting such events and assist with further research in this area.

Earthquake prediction

The Earth's magnetic field can be influenced by natural events, such as tectonic plate movement and earthquakes. Magnetic pulses have been observed prior to earthquakes and could potentially be used to predict earthquakes (Scoville, Heraud and Freund, 2014).

Animal migration

It is important to understand changes in the Earth's magnetic field as many organisms living on Earth rely on the magnetic field for navigation. For example, birds are able to detect the magnetic field and use it as a compass both for short distances and long migrations (Pinzon-Rodriguez, Bensch and Muheim, 2018).

Climate effects

Long-term changes in the magnetic field have also shown to be correlated with cooling in the thermosphere. These changes are not uniform across the globe so it would be valuable to have multiple data points to study the long-term trends (Cnossen, 2014).

Anthropogenic effects

While space weather is dominated by the Sun, human activities have been shown to have an impact on the Earth's magnetic field. A recent paper highlighted the effect of Cold War atmospheric nuclear tests on the magnetic field, and also discussed how VLF radio transmissions from Earth have expanded the Van Allen radiation belts. This study shows how important it is to understand the implication of human activities on the Earth's space environment (Gombosi et al., 2017).

6.1.2.2 Commercial

Space weather, particularly large geomagnetic storms, can impact both Earth-based and space-based infrastructure. These adverse effects ultimately result in an economic cost that can be attributed to space weather. High spatially distributed data obtained by ChipSats could help enhance the accuracy of prediction models that provide early warning for extreme solar events. Improving the accuracy of such models would have commercial value as it enables operators to take action to protect their infrastructure from the impacts of space weather events. Some of the major impacts, with associated economic costs, are discussed below.

Satellite disruption

Modern society is heavily reliant on satellite-based communication and navigation, both of which can be severely disrupted by space weather events (Chen et al., 2019). The solar wind directly influences the Earth's magnetic field and can interfere with orbiting satellites, changing their orbits and damaging electronics. The effects can range from an hour-long service disruption to the complete loss of a satellite. This results in significant cost and lost revenue to the operator, as well as dissatisfied customers. It is very difficult to determine whether space weather is responsible for a satellite anomaly which is where in-situ measurements could be useful (Horne et al., 2013).

Ionospheric disturbance

Space weather-induced disturbances in the ionosphere can affect RF signal propagation. This affects users of radio communication such as the military, emergency services, and commercial air traffic in the polar regions. In addition, ionospheric disturbances can limit the accuracy of navigation signals from satellites, affecting many users including air traffic control and ship navigation (Lanzerotti, 2007).

Electricity black outs

There are several recorded instances of space weather causing outages in electricity transmission systems. A recent study has analyzed the potential financial impact on the United States of an extreme space weather event. For an event resulting in 8% of the population losing power, the economic loss to the US economy would be US $6.2 billion per day (Oughton, 2017).

6.1.3 Mission Design

The mission objective is to collect high spatially distributed in-situ magnetic field measurement from LEO during large solar events. This will involve hundreds of ChipSats deployed from a CubeSat when a solar event is predicted or detected. The data collected during these periods can be used for heliophysics research and calibrating space weather forecasting models.

As such, the data obtained has to comply with the requirements imposed by the scientific community. Observing Systems Capability Analysis and Review Tool (OSCAR) database managed by the World Meteorological Organization (WMO) provides the following operational requirements for measurements of the magnetic field (WMO, 2020):

1. Horizontal resolution: 10 km
2. Timelines: 60 sec
3. Observing cycle: 10 sec
4. Uncertainty: 0.3 nT

The following mission concept was created to address the mission objectives while particularly emphasizing the importance of obtaining distributed measurements simultaneously. Figure 6.1 below illustrates the mission.

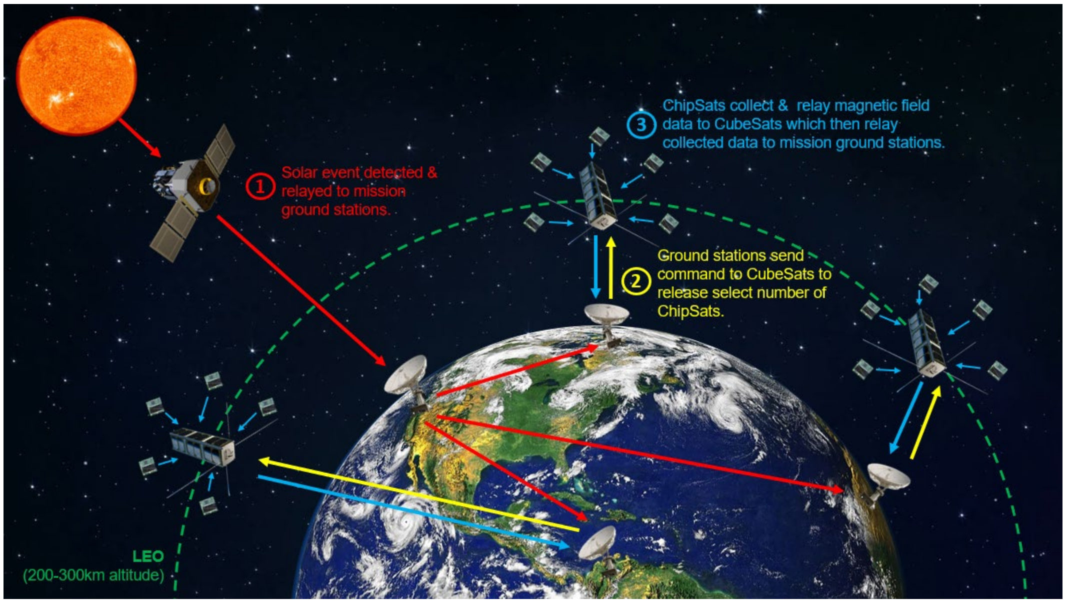

Figure 6.1. Space weather mission architecture overview

There are several ways to make measurements of atmospheric and space-related phenomena such as Earth's magnetic field with satellites. The novelty of using ChipSats for this mission is the ability to use a large number of them, hence measuring a wide band in space simultaneously, compared to the limited data that can be measured by a single satellite.

The selected architecture of this mission is to have a hosting CubeSat, which will have a large number of ChipSats embedded inside. Once engaged, this CubeSat will use an internal mechanism to release the ChipSats with a delta-V, which will push them away from it. The ChipSats will be released circularly relative to the CubeSat, so after some time there will be an area of them covering a wider band as demonstrated in Figure 6.2 below. The differentiating factor of this mission is the wide sample area and the density of ChipSats within it.

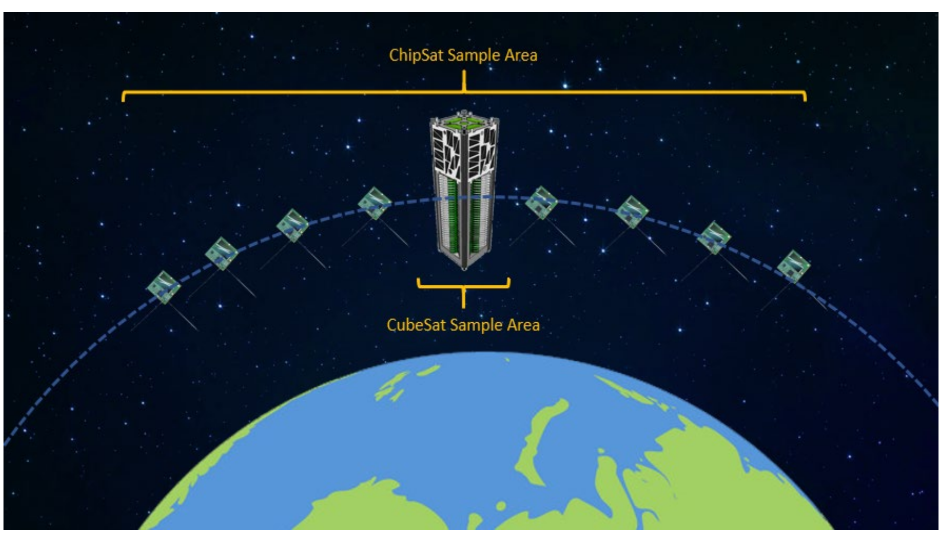

Figure 6.2. Illustration of ChipSat wide sample area

An important mission consideration is the number of hosting CubeSats. The larger the number of CubeSats launched, the more bands of ChipSats will be available to sample more points simultaneously. The scientific value of adding further CubeSats will need to be weighed against the available budget.

Each of the released ChipSats will have a measurement unit (magnetometer), a precise IMU and a communication subsystem necessary to assure the ChipSat's operation and survival. The ChipSats will communicate with the CubeSat, which will later on relay their information to a ground station and a central computer.

The deployment system is recommended to be selective and mechanical (e.g. by means of a spring), and giving the ChipSat an angular velocity parallel to the normal ChipSat vector (e.g. by giving the CubeSat a high angular velocity). This will assure a gyroscopic motion that will maintain the ChipSat orientation. By doing this, the satellite photovoltaic cells will point to the Sun during most of the ChipSat lifetime, which will permit the system to be fed with enough energy for the entire operation. Because of technological limitations, no batteries will be installed.

The deployment spacecraft(s) will orbit the Earth at an altitude of 200 - 300 kilometers in a circular orbit with a recommended high inclination to cover most of the Earth’s atmosphere. For a measurement to be taken, a set of satellites will be deployed, and they will get away radially and gradually covering a higher measurement area as a function of time. At that altitude, the orbital decay time is between days and weeks due to their low ballistic coefficient. The KickSat-1 sprites predicted the decay time for various drag cases with the results shown in Figure 6.3 below (Manchester, Peck and Filo, 2013).

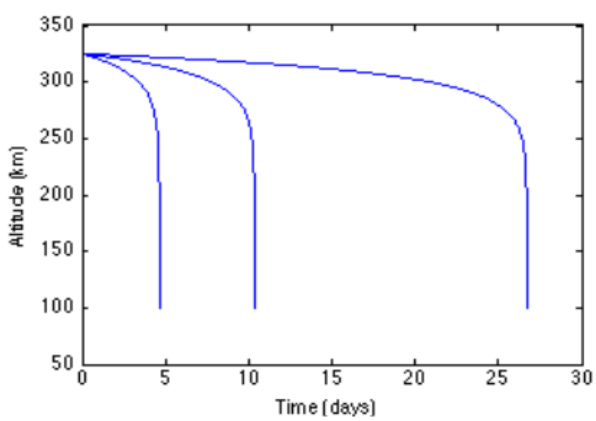

Figure 6.3. Altitude vs Time for KickSat-1 Sprite in LEO (Manchester, Peck and Filo, 2013)

Deployment spacecraft requirements:

1. Capable of storing and deploying by mechanical means 200 ChipSats
2. Delta-v for station keeping in LEO (300 kilometers) for 12 months and assuring end-of-life
3. Operational lifetime of 12 months
4. System has to provide 3-axis stabilization and orientation of approximately one arc minute accuracy
5. Horizontal position determination of 1 km

6. Enough gyroscopic motion transmitted to ChipSat to assure photovoltaic orientation to the Sun

ChipSat requirements:

1. Horizontal position determination of 1 km + 3 km / day in orbit
2. Capability of communicating to the deployment spacecraft of a ground station to transmit sensed data
3. Magnetometer with an accuracy of 0.3nT away from interferences of the ChipSat
4. Survivability (does not mean operability of the ChipSat) during eclipse phases of the orbit. No operation will be required in these phases

Table 6.1 below outlines the ChipSat subsystems and capabilities.

Table 6.1. ChipSat subsystems and approximate capabilities

Component	Mass or Mass/unit area	Power	TRL
Microcontroller	<1.0 g	10 - 20 mW	7/8
6-axis IMU	<1.0 g	2.0 mW	8
Kapton PCB	0.06 g/cm²	0 mW	9
Transceiver	<1.0 g	10 mW	8
Omnidirectional antenna	1.0 g	N/A	7
Magnetometer	<1.0 g	30 mW	7
Photovoltaic Cell	0.084 g/cm²	N/A	8

6.1.4 Key Technological Challenges

There are a number of technical challenges associated with the proposed mission concept that will need to be solved in further stages of development. For now, the challenges have been briefly described with some suggestions of potential solutions.

Challenge 1: Position Determination

Since the ChipSat can have a limited number of position-determination sensors (no star or sun-trackers can be fitted nowadays), a reliable substitute has to be found. A possible solution can be to install a high-performance position determination system in the spacecraft that will deploy the ChipSats, where the CubeSat can have a sun or star-tracker. The ChipSat will then calculate its relative position compared to the original spacecraft by integrating the gyroscope and accelerometer measurements of an IMU. Two problems have been identified to this solution: the first is that inaccuracies in the inertial measurements will result in a position error that will increase quadratically as a function of time. Moreover, if the system does not take enough measurements (because of energy limitations), the position will no longer be reliable.

Challenge 2: Precise Magnetic Field Measurement

Achieving precise measurements away from electromagnetic influences produced by other components will be a challenge within the limitations of a ChipSat. An accuracy of 0.3nT has to be achieved, meaning that the noise has to be reduced, to at least 0.3nT.

Three solutions are proposed. The first is to modelize the magnetic field produced by the electronic components and subtract with the measurement taken by the magnetometer. This solution can be difficult to implement since the electromagnetic field produced by the different subsystems is highly dependent on many external factors (such as radiation) that cannot be predicted. A second solution is to design a deployment system that will put the sensor away from the influence area of the other components. The team proposes to install a mechanical deployment system activated by electronic means, rather than a fully electronic system to minimize source of possible errors and energy-consuming subsystems. Further analysis must be done to determine the feasibility of this and to determine the distance at which the sensor has to be placed. A third solution consists of shutting the different components down during the time that the magnetometer measures the magnetic field around the Earth.

6.1.5 Commercialization

Space weather impacts infrastructure both on Earth and in space with an associated economic cost, such as damage to infrastructure or lost revenue. Therefore, any new data that helps to better understand or mitigate against space weather has value that can be utilized by commercialization.

6.1.5.1 Potential Customers

There are a variety of organizations that will be willing to pay for the data acquired by the proposed ChipSat mission, as it can provide some economic or scientific value to them. The main anticipated customers of the magnetic field data are described in this section.

Space Weather Forecasters

New magnetic field data from the proposed ChipSat mission may be of interest to organizations developing forecasting models. Such high spatially distributed data can help calibrate the models to improve accuracy, as more measurements inside the geomagnetic field help to reduce the uncertainty of forecasts (Black, 2017). Forecasting models can provide a one hour notice of an extreme solar event and allow time for protective or preparatory action to take place. Examples of organizations that benefit from such forecasting models include satellite manufacturers and operators, electricity networks and air traffic control.

There are many organizations involved in developing forecasting systems aimed at providing advance warning of potentially damaging space weather events. The United States National Oceanic and Atmospheric Administration (NOAA) manages the Space Weather Prediction Center (SWPC) which produces forecasts for a variety of space weather events. The forecasts are freely available online for anyone to access in a range of formats. The forecasts are generated by a collection of computer models developed by various scientific and academic organizations (NOAA, 2015). In Europe, the SPACE STORM project developed computer models to forecast space weather and its effects on a range of orbits. The project was funded by the EU with the specific goal of protecting the Galileo space assets (European Commission, 2014).

Insurance Companies

The Cambridge Centre for Risk Studies conducted an economic analysis of the potential costs associated with an extreme space weather event. The study was supported by insurance company AIG, and aimed at those wanting to understand their risk exposure when calculating the anticipated number and cost of insurance claims associated with such an event (Oughton et al., 2016). Insurance companies will likely be a secondary customer as they rely on published reports such as the one mentioned above, rather than purchasing and analyzing the raw data themselves.

Space Agencies (Science)

Solar and heliospheric physics are receiving significant interest and funding from space agencies, as demonstrated by two recent missions. The $1.5 billion Parker Solar Probe operated by NASA was launched in August 2018 and has traveled closer to the Sun than any other spacecraft (NASA, 2018). In addition, the Solar Orbiter mission, a collaboration between NASA and ESA, launched in February 2020 has a budget of approximately €1.5 billion, which equates to approximately $1.7 billion (Wall, 2020).

The data from the Solar Orbiter is intended to supplement the data from the Parker Space Probe, by providing in-situ data from different vantage points. Together, the missions will help provide a better understanding of solar physics, including the Sun's magnetic field and solar wind (Wall, 2020). These missions demonstrate the willingness of space agencies to pay for data relating to space weather, such as the measurements collected by the proposed ChipSat mission.

Space Agencies (Situational Awareness)

Space agencies are particularly interested in predicting large solar flares as they can be hazardous to astronauts, airplane passengers, and spacecraft. The ESA's Space Situational Awareness program plans to establish a Space Weather Network. The Distributed Space Weather Sensor System (D3S) plans to collect in-situ measurements using a combination of hosted payloads and dedicated SmallSat missions. These measurements are intended to be used for satellite operation, event analysis, and space environment studies. The hosted payloads refer to instruments hosted by spacecraft being flown for purposes other than space weather monitoring (ESA, n.d). However, instead of using SmallSat missions or hosted payloads, ChipSats may be used to obtain some of the required measurements.

World Meteorological Organization

While unlikely to be a customer themselves, WMO supports international coordination of monitoring and forecasting activities relating to Space Weather. It publishes its Guidance for Space Weather Observations and maintains an accurate database of satellites plus the instruments available onboard for observations (WMO, 2017). In the 2017 Statement of Guidance for Space Weather Services, the WMO stated that "overall spatial coverage and the temporal resolution of the global-scale magnetospheric magnetic field data needs to be improved and in its current state should be classified as poor" (pp 19). It also stresses that "the timely (real-time) availability of operational geomagnetic data is, perhaps, the most critical requirement in the space weather monitoring and forecasting services" (pp 19).

6.1.5.2 Competitors

ChipSats are ideal for missions that require a large number of units with limited functionality, for a short amount of time. Using larger satellites for this type of mission will result in significantly higher costs.

The proposed ChipSat mission concept for measuring the Earth's magnetic field in relation to space weather events will have several competitors, as described below.

CubeSats

The larger size of CubeSats enables higher quality sensors, larger power supply / storage, and more powerful communication systems. This results in better data, but costs much more for the same number of satellites. However, customers may choose to have fewer, more capable satellites to measure the magnetic field.

Existing Satellites

There are currently numerous satellites in Earth orbit with magnetometers onboard. This data is available to customers already, and may sufficiently satisfy their need for data, making the ChipSat network obsolete.

Ground-Based Measurements

Using magnetometers on the ground is a much less expensive and simpler option for customers. It is possible to have a network to measure the magnetic field for multiple locations simultaneously (Mandea, M. and Isaac, A., 2011). Obviously these measurements are only available at surface altitude rather than in orbit so may not be suitable for all customers.

Hosted Payloads

Instruments flown onboard other satellites, such as the hosted payloads proposed by ESA, may enable better measurement than a ChipSat can provide (ESA, n.d). However, this approach is limited to only a small number of spacecraft and may not provide measurements at the locations required.

While the above technologies have been identified as competitors, it is possible to combine multiple methods together to achieve a larger data set of magnetic field data. For example, ESA has proposed using CubeSats with hosted payloads to provide all the measurements they require (ESA, n.d).

6.1.5.3 Revenue Streams

The main revenue from the proposed ChipSat application will come from selling the magnetic field data collected. There are three potential opportunities for revenue streams which include subscription-based services, pay per download services or external funding. The best suited revenue stream will depend on the type of customers and their needs.

Subscription Model

A subscription-based revenue model involves charging customers with a monthly or yearly fee to access the collected magnetic field data (Campbell, 2019). In the domain of subscription-based services, the raw or processed data will be made available on a cloud platform to allow easy accessibility for customers to download and process the required data as needed. Customers will also have access to a growing archive of data which, for example, can be used for visualization of trends (Planet, 2020).

This type of revenue stream would be ideal for customers requiring constant up-to-date data such as space weather forecasters, satellite manufacturers, electricity networks, and air traffic control. Subscription-based services would provide most reliable and steady streams of revenue for this ChipSat application. However, this means that the ChipSats have to be able to provide reliable and accurate data in a timely manner, which may not be initially possible with the current technological restrictions. As ChipSat technology continues to improve, subscription-based services may prove to be excellent revenue streams for collected magnetic field data.

Pay-Per-Download

Pay-per-download, or one-off purchase, is another potential revenue stream which involves directly selling, in a single transaction, a specific set of data to a potential customer. Current ChipSat technology readiness would make this an ideal revenue stream once the ChipSat application is well established and interest has been shown by potential customers. A pay-per-download revenue model would be ideal for customers such as insurance companies or space agencies (science) requiring space weather data for research and understanding general characteristics and risks associated with space weather.

External Funding Sources

External funding sources can pay for the entire mission up-front, rather than providing a continuous revenue stream. External funding sources can come from crowdfunding efforts, venture capital funds or scientific grants. Sources of scientific grants can include government agencies, research institutions, national foundations or corporations (Milner, 2015). It is important to keep in mind that with external funding, the nature of this potential ChipSat application will be non-profit. External funding is an ideal method of funding the initial development of the proposed ChipSat application to provide a proof of concept and assess the market demand for distributed magnetic field data measurements.

6.1.5.4 Cost Estimate for Mission

In order to estimate the mission cost, the following variables have been considered:

ChipSat cost (200-1,000 units)

A good reference for a ChipSat cost is Sprite, which is $300 (Manchester, 2013). It can be assumed that with the addition of one day work for integration and testing (8 hours x $20 = $160), the total cost of a single ChipSat will be $460.

Note: In this model, it is assumed that the AmbaSat kit will have all the components required for this mission, hence it does not include the development costs for the ChipSat.

CubeSat cost (1-5 units)

According to Alén Space, their 'A Basic Guide To Nanosatellites' states that a nanosatellite can not only be built but also placed in orbit for less than €500,000 (Alén Space, 2020), or around $567,000. It can be assumed that this price is built from 70% development efforts, 20% production and 10% launch costs. Hence, the non-recurring expenses for this mission will be $350,000 and the recurring expenses of the CubeSat including its launch will be $150,000.

Ground segment cost (1-5 units)

The mission can use a turn-key ground station such as the ISIS Small Satellite Ground Station for which the off the shelf cost is $67,000 (ISIS Full Ground Station Kit for S-band).

Development of the integration software

The integration software goal is to collect all ChipSat data and create the magnetic field model. It is estimated to be a relatively simple software model which only requires a standard PC. Development efforts of this software are estimated to be 12 months.

Total costs for this mission are shown in Tables 6.2 and 6.3 below.

Table 6.2. Model 1 - Single CubeSat, single ground station

Item	QTY	Cost	Comments
CubeSat Non-Recurring Expenses.	1	$350,000	
CubeSat + 200 ChipSats: production + launch costs.	1	$238,000	
Software Development: 12 months.	1	$100,000	$50 per hour.
Ground Segment.	1	$67,000	ISIS Small Satellite Ground Station.
Labor (management, procurement, legal): 12 months.	2	$120,000	$30 per hour.
Sub Total:		**$875,000**	

General and administration, miscellaneous, unexpected: 30%.		$262,500	
Profits: 15%.		$170,625	
Total costs:		**$1,308,125**	

Table 6.3. Model 2 - Six CubeSats, three ground stations.

Item	QTY	Cost	Comments
CubeSat Non Recurring Expenses.	1	$350,000	
CubeSat + 200 ChipSats: production + launch costs.	6	$1,428,000	$238,000 each.
Software Development: 12 months.	1	$100,000	$50 per hour.
Ground Segment.	3	$201,000	ISIS Small Satellite Ground Station, $67,000 each.
Labor (management, procurement, legal): 12 months.	2	$120,000	$30 per hour.
Sub Total:		**$2,199,000**	
General and administration, miscellaneous, unexpected: 30%.		$659,700	
Profits 15%.		$428,805	
Total costs:		**$3,287,505**	

6.1.5.5 Key Mission Risks & Assumptions

The major mission risks that may compromise mission quality or prevent mission success were considered and are outlined below. Following ESA's Scientific Directorate Risk Management guidelines (Schroeter, 2001), the risks are ranked according to their risk level based on likelihood and consequence within a risk matrix (Figure 6.4). Mitigation and avoidance techniques are identified, as seen in Table 6.4, for the risks whose rating surpasses the acceptable risk index threshold of 3C and ranked in an updated risk matrix (Figure 6.5).

R1 - TRL

This mission has been proposed with the assumption that the TRL of the required ChipSat components, including the primary payload, is or can be brought to an acceptable level in a reasonable amount of time. Should this not be the case, there will be major implications for scheduling and cost overruns.

R2 - ChipSat Survival

It is assumed that ChipSats will be able to survive in a dormant state within the CubeSat for at least one year. If this is not the case, the mission duration may be cut short compromising main mission objectives.

R3 - Launch Licensing

According to a consultation with Zachary Manchester, developer of the first ChipSat mission called KickSat, obtaining proper clearances and licenses for launch is both a major challenge and risk due to the issue of space debris. It is difficult to find a launching state that is willing to take liability for Earth-orbiting ChipSat launches.

R4 - ChipSat Deployment

The inability of the CubeSats to deploy the ChipSats in a timely manner could pose another threat to the entire mission. This risk could be a result of issues in communication with the CubeSat or the ChipSats deployment mechanism.

R5 - In-Orbit Collision

There is a possibility of in-orbit collisions with other spacecraft in LEO. This is primarily due to the lack of a propulsion system onboard the ChipSats as well as the possibility of being unable to track the location of ChipSats should they become damaged and stop working.

R6 - Magnetic Field Data Accuracy

There is a possibility of obtaining inaccurate data from the magnetometer measurements due to the electromagnetic interference from the ChipSat components which are located in extremely close proximity to the magnetometer.

R7 - Position Determination Precision

Knowledge of the location of where magnetic field data is being measured to an acceptable precision is important for the mission. Position of ChipSats can be determined relative to their mothership, however inaccuracies in inertial measurements and lack of measurements over a period of time will lead to unreliable position data.

R8 - ChipSat components or systems failure

The possibility of ChipSat Electrical, Electronic and Electromechanical (EEE) COTS component or systems failure must be taken into consideration.

R9 - CubeSat components or systems failure

The possibility of CubeSat EEE COTS component or systems failure must be taken into consideration. CubeSat subsystem failures are important to take into consideration as it is the main communication link between the ChipSats and ground stations.

R10 - Communication Loss

There is a possibility of failure for the CubeSat communication subsystem, which tends to be one of the common failures among CubeSat missions in general. In this case, data collected by ChipSats cannot be retrieved by the ground stations.

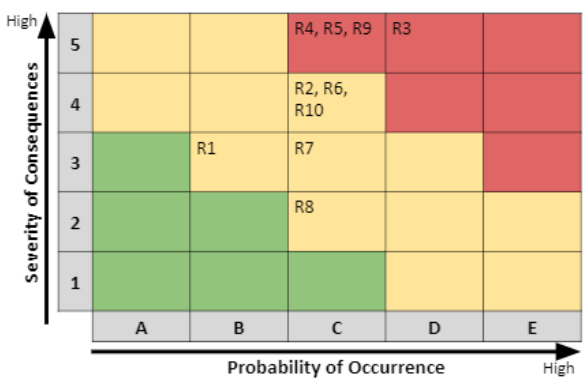

Figure 6.4. Space weather mission risk matrix displaying levels of various risks before mitigation.

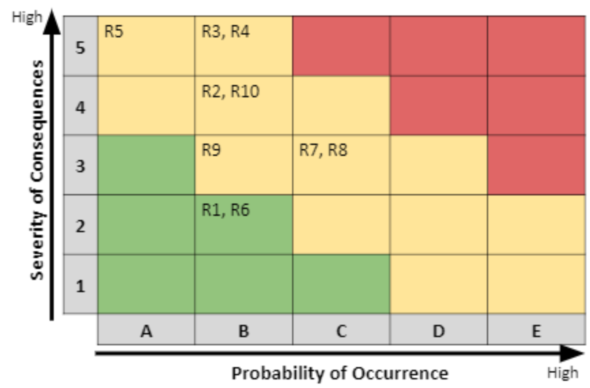

Figure 6.5. Space weather mission risk matrix displaying levels of various risks after mitigation.

Table 6.4. Space weather mission risk mitigation strategies

Risk	Control Measures
R1	Acceptable risk
R2	1. Ensure robust radiation shielding / protection of CubeSat to protect ChipSats within 2. Conduct robust radiation testing of CubeSat and ChipSat critical components
R3	Consider multiple potential launching states from which to obtain licensing other than the USA
R4	Perform robust testing of deployment mechanism including vibration and shock tests Ensure redundancy for deployment command (automatic timers and manual override options)
R5	Ensure ChipSats are deployed in a very LEO with altitude between 200 km to 300 km
R6	Develop, implement and test one of three solutions mentioned in section 6.1.4 to reduce ChipSat component noise to acceptable levels
R7	Acceptable risk
R8	eptable risk
R9	Ensure redundancy for critical subsystems Ensure reasonable margin for power, communication and propulsion subsystems Conduct thermal finite element analysis on all electronics and PCBs
R10	Perform high-altitude balloon test on CubeSat prototype Test any onboard antenna deployment systems

6.1.6 Future Research & Applications

There are a variety of future research and applications that can benefit or be made possible from mission concepts derived from this space weather mission. These future applications include different types of missions that can benefit from distributed magnetic field measurements and similar missions for various types of atmospheric measurements. Some of these future applications and the corresponding research required are discussed in this section.

6.1.6.1 Additional Magnetic Field Missions

ChipSats containing magnetometer payloads and possessing the capability of being able to obtain distributed magnetic field data can be applied to many different types of mission scenarios to understand different types of phenomenon or effects of space weather in different near Earth locations.

Aurora Borealis

An example of a particular phenomenon of interest are the Aurora Borealis, also known as the Northern and Southern Lights, as described earlier in Section 6.1.2.1. Multi-point measurement capabilities of the magnetic field in the region of the auroras combined with ground-based measurements and observations will allow for detailed investigations into the nature of the phenomenon while advancing space weather research (Parham et al., 2016).

South Atlantic Anomaly (SAA)

Another phenomenon of interest includes the SAA which is an area close to the surface of the Earth with a relatively weaker magnetic field and correspondingly high radiation environment. It is crucial to obtain multiple spatially and temporally distributed measurements, preferably from different orbital planes, to construct dynamic models of the geomagnetic field. The need for high-quality and resolution geomagnetic data is fundamental to understanding the dynamic evolution of the SAA (Pavón-Carrasco and De Santis, 2016).

Van Allen Belts

Another potential application for similar ChipSat missions is to collect distributed multi-point measurements within the Van Allen Belts to better understand the magnetic field and radiation environments. The Van Allen Belts are a result of high-energy particles emitted from the Sun getting trapped due to Earth's magnetic field as well as interactions between cosmic rays and the Earth's atmosphere (Garner, 2018). Being able to understand the dynamic environment of the Van Allen Belts can prove to be extremely useful for technology design and future human spaceflight missions (Garner, 2018).

The major challenges associated with accomplishing such missions are the current limited ChipSat capabilities such as lack of propulsion system, which poses great bureaucratic space debris tracking and mitigation issues, and lack of radiation protection. With the future advancement of ChipSat technologies in overcoming these challenges, there are many important applications present beyond LEO.

6.1.6.2 Additional Payloads to Consider

Apart from magnetic field measurements, there are several other measurements of interest to understanding the various phenomenon of space weather and of interest to many of the potential customers mentioned in Section 6.1.5.1. Many of these measurements could benefit from in-situ distributed sensor networks offered by ChipSats.

Plasma Measurements

Plasma measurements made by distributed sensor networks can provide insightful information regarding space weather and solar activity. Langmuir probes are the most popular type of plasma instruments that have been used aboard many spacecrafts to obtain information about plasma density, temperature and velocities (Peitso, 2013).

Electric Field & Electrostatic Measurements

Electric field measurements, such as average electric field and density, are also important in order to understand space weather related events as well as the plasma environment. One example of such an instrument is the Cluster Electric Field and Wave (EFW) instrument installed and operated onboard the Cluster satellite mission. The measurement of charged particle energy distributions are another set of measurements that can be taken with the help of electrostatic analyzers (Peitso, 2013).

Radiation Measurements

Radiation detectors are another popular instrument found aboard many satellites to understand radiation environments as well as how they are affected due to solar activity. Radiation detectors are able to provide information about particle types and corresponding incident energies (Schiller and Mahendrakumar, 2010). Information about radiation environments, while very useful for previously mentioned customers, is also extremely valuable for human spaceflight missions.

The main limitation in being able to obtain different types of space weather related measurements is the large size and mass of the required instruments which are not yet designed to be used onboard ChipSats. The design of many of these instruments have not been updated accordingly due to a lack of need as can be seen with electrostatic analyzers whose design has not been updated since their invention in the 1920s (Peitso, 2013). However, validation of the usability of ChipSat technology and distributed sensor systems has the potential to spark the need to redesign and miniaturize such instruments.

6.1.7 Legal Implications

There are many legal implications of the proposed ChipSat mission to gather magnetic field data from LEO. The major issues to consider will be discussed in this section.

Free Access to Space

The legal ability of a commercial entity to obtain licenses to launch and manage such a mission is assured in the OST which states that “outer space shall be free for exploration and use by all States, the exploration of it shall benefit and be of interest for all the countries" (Outer Space Treaty, 1967). As such, any legal entity, whether it is a commercial or educational one, will have the right to pursue and execute this mission, as long as it obtains the needed licenses and is aware that it is subject to the local country's supervision.

Space Debris

This mission, which involves hundreds of ChipSats, will result in a large number of tiny satellites orbiting the Earth that are difficult to detect. These objects may create a tangible danger to other satellites and orbiting bodies, therefore their end of mission should be handled with care. In order to minimize the debris risk, this mission plans to place the ChipSats in a very low orbit (200-300 kilometers), where the orbital decay time will be approximately one month. After this time, the orbit of the ChipSats will have decayed and they are expected to burn up in the Earth's atmosphere.

Usage of Export-Controlled Components

ChipSats are miniaturized satellites and incorporate various components and technologies that could have dual use for commercial and military applications. Obtaining export licenses, which are subject to end-user and end-use declarations, is a common process for defense systems and applications. Yet, in order to simplify the operation and complexity of this mission, it is highly recommended to use only COTS commercial-grade components that are free from any export control regulation.

Complexity of the Legal Framework

In order to simplify the operation of this mission, it is recommended to minimize the number of States that are involved and considered to be launching States. The State that the mission company is registered in is defined as a launching State. However, other States may also be defined as such, including a State from which the launch was performed, and a State to which the company performing the launch belongs to. This means:

1. Once the mission is ready, it is recommended to make the final assembly at the same State from which the launch will take place.
2. The mission stakeholder should consider buying and owning both the CubeSats and the ChipSats, otherwise the country from which the CubeSat was produced will be involved as a launching country.

Cyber Security

ChipSat missions will need to consider the same precautions as large satellite operators to engage in commercial space operations with regards to data transfer encryption and network access. Small satellites are vulnerable to cyberattacks in a number of ways; networks can be breached, controlled, and disabled. While the size, utility, and limitations in navigational capability of ChipSats prompts the "What's the worst that could happen?" view, there must be a balance between the capital investment and cost of encryption for low-cost, small satellites (Werner, 2018).

If the ChipSat deployer is hacked by unauthorized actors, the following scenarios seen in Table 6.5 below could result in a loss of value for the mission.

Table 6.5. Cybersecurity threats to mission

Unauthorized Actor's Actions	Outcome
Controls disbaled	Cannot complete mission Reliant critical infrastructures, systems, and surface networks impacted.
Access held for ransom	Economic loss Reputational damage Data breach Reliant critical infrastructures, systems, and surface networks impacted
Redirection of deployment CubeSat orbit	CubeSat potentially used as a Kinetic Kill Vehicle (KKV). CubeSat orbited off target leading to economic loss Reliant critical infrastructures, systems, and surface impacted

At a minimum the ChipSat deployer can be disabled, resulting in a financial loss as the mission cannot be completed. On the other extreme end, hacking lends its way to turning a CubeSat, such as the ChipSat deployer, into a KKV where unauthorized actors can target and destroy high-value spaceborne assets in contact (Kurzrok, 2018). At high speed, collisions with small objects can result in extensive, if not permanent damage to nearby military, commercial, or scientific spacecrafts. Thus, the LIAB can be invoked with the secondary lunar mission objective (UNOOSA.a., 1971):

1. Single State launch - Article VIII paragraph 1: "A State which suffers damage, or whose natural or juridical persons suffer damage, may present to a launching State a claim for compensation for such damage."
2. Two-or-more-State launch - Article IV paragraph 1b: "If the damage has been caused to a space object of the third State or to persons or property on board that space object elsewhere than on the surface of the Earth, their liability to the third State shall be based on the fault of either of the first two States or on the fault of persons for whom either is responsible."

6.2 Lunar Communications Mission

6.2.1 Introduction

Lunar communication is a vital component for future rover activities on the Moon. As the search for water ice propels research and technology development forward, previously untouched and unreachable regions are being explored by various rover missions, carried out by both commercial actors and national space programs. Lunar communication addresses the potential line of sight communication gaps for rovers entering craters or lava tubes, providing relay options and mission specific deployments.

6.2.2 Mission Justification

A temporary deployable Low Lunar Orbit (LLO) ChipSat network can provide added communication coverage for rover activity on the lunar surface and within craters or lava tubes. Several CubeSat and rover missions are expected in the coming two to five years which will both enhance the resolutions of lunar surface mapping, and test new communication protocols and technologies. ChipSats offer a low cost option for communication relays with a CubeSat or Gateway, when line of sight with the rover is interrupted. Secondary benefits to the deployment can be obtained through planned de-orbit (end-of-life) suicide missions communicating sensory data from within lunar craters. Examples of identified high value lunar scientific targets can be seen in Figure 6.6 below.

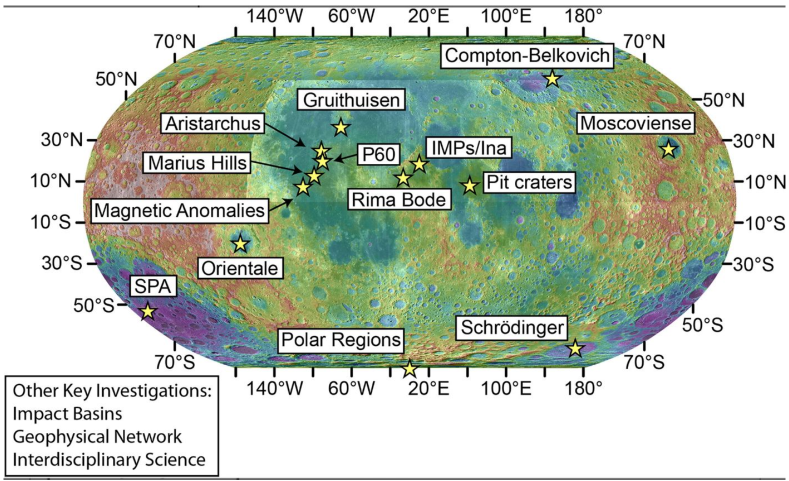

Figure 6.6. High-priority lunar landing sites by scientific ranking (Jawin, et al., 2018)

6.2.2.1 Scientific Value

Given a secondary mission objective of ChipSats is planned deorbit within craters, additional data sets via sensor readings can be taken to augment the primary data captured by other spacecrafts or rovers. ChipSats offer the necessary trade-off of quantity, not cost, to decrease mission failure risks. Examples of research areas where new data from LLO ChipSats and planned deorbit sensing could be used are documented below.

Impact survival testing

While ChipSats offer neither the mass nor the velocity with which meteorites bombard the lunar surface, they can provide some measurement of lunar impact survival testing. Thus far, these tests have only been conducted in simulated environments. Gaining a clearer understanding of the impact, displacement and settling of lunar dust can also inform impact crater processes. As part of the end-of-life planning, rovers will be distributed to “collect” the ChipSat debris while carrying out mission objectives.

Radiation environment

Detection of radiation levels in deep space environments is crucial to understanding the human risks from deep space travel beyond the Moon. The development of microscale sensors to detect radiation levels as the ChipSats deorbit would be a useful addition to human exploration knowledge gaps. The data can help in planning for both long duration spaceflight and in determining the necessary countermeasures needed in lunar settlement plans. There are two possible options for the sensors. The first is a low power nanotube chemical sensor developed by NASA AMES which provides a technology with possibilities, though the size is still above the current limitations for a ChipSat as seen in Figure 6.7 below (Li, et al., 2016). The second is a graphene bolometer with ultrahigh temperature coefficient resistance as seen in Figure 6.8 below, but size is also an area needing further consideration (Sassi, et al., 2017).

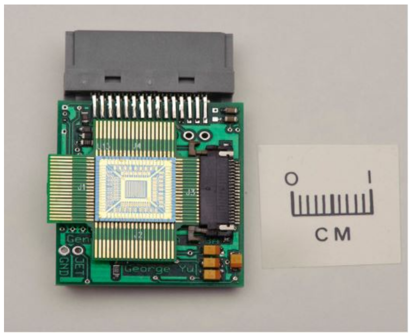

Figure 6.7. Carbon nanotube chemical sensor (Li, et al., 2016)

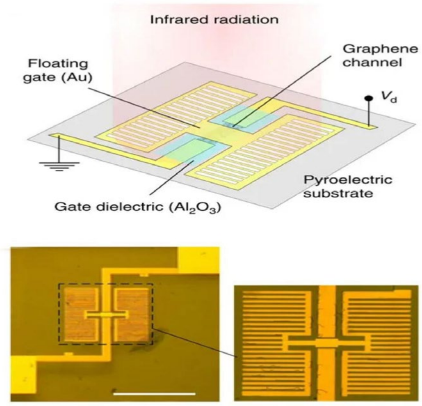

Figure 6.8. Graphene bolometer (Sassi, et al., 2017)

Lunar tectonism and seismicity

Adding to the impact survival testing, deorbiting on the far side of the Moon may allow for the ChipSats to act as passive seismometers assisting in detection for the lunar geophysical network (Jenner, 2019). Understanding the interior structure of the Moon, as well as understanding the propagation of seismic waves is a key metric to forecasting for lunar mining and settlement locations. A nano-g micromachined seismic sensor, as seen in Figure 6.9, may provide a starting point at 0.31 g, but advances in either miniaturizing the full MEMS package or developing an alternate encasement system to protect the board (protective method) must be realized before deployment will be possible (Wu, et al., 2018).

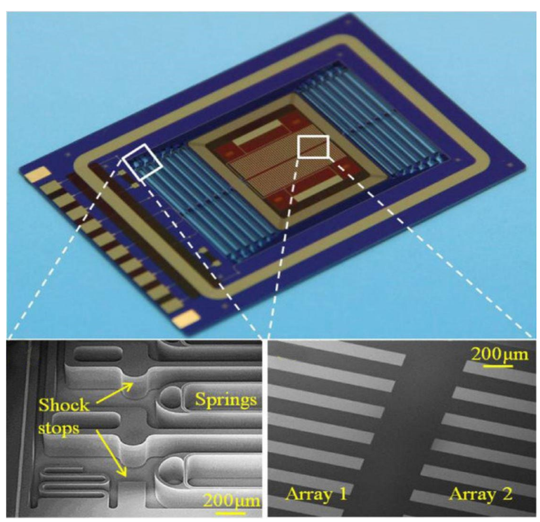

Figure 6.9. Nano-g micromachined seismic sensor (Wu, et al., 2018)

Heliophysics

The origin of regolith materials are both lunar and extra lunar and little has changed since the time that they settled. Understanding how these react to solar winds along the geologic timescale can lead to a better understanding of the Sun's history and behavior over time (Usoskin, 2017). As such, lunar programs pertaining to settlement or human exploration can be adapted accordingly regarding radiation protections or early warning systems.

6.2.2.2 Commercial Value

As the search for water ice at the lunar poles pushes ahead, both satellite and rover missions prepare to explore regions previously untouched and unreachable. Planning for commercial ventures set to explore the lunar surface are well underway, including a short list with launch dates within the next two to five years (Hakamada, 2019) and (Howell, 2019). Temporary ChipSat deployments can provide a data transfer assist when the mission operations of rovers entail suspension over crater edges or exploration deep within a shadowed crater or lava tube. The data derived from these missions will inform the commercial applications and companies that seek to extract and refine it into usable O^2 and ultimately move humanity into deeper space.

Satellite communication disruption

Operating rovers in craters or lava tubes can pose challenges for communication links. Space weather can also effectively cripple CubeSat communication links. With a deployed ChipSat network, partial survival of the weather event and continued operation of even a few ChipSats would provide a needed backup communication link. In this way, the sheer numbers deployed would represent a statistical predictability of survival. Maintaining operability with the lunar rovers would ensure the successful completion of each commercial or agency mission.

Mapping surface features and internal composition

Creating more detailed maps of the water-ice deposits has the potential of bringing in commercial operations to the Moon for extraction and refinement, much like terrestrial mining operations. Autonomous vehicles and robots can be employed to do the heavy lifting, but a robust Moon economy can be imagined with technology transfer benefits between both Moon and Earth.

Lunar seismology

Future Moon settlements will draw upon the plethora of new science derived from lunar missions over the next five years. The lunar geophysical network and its findings can affect the choice of settlement location and mining operations. Similar to the scientific benefits listed previously, the data holds value for the commercial enterprises looking to choose sites for their operations based on statistical data, risk assessments and contingency plans.

6.2.3 Mission Design

The network of ChipSats deployed in LLO can help create a temporary backup communication network between a rover on the lunar surface or in a crater and the relay satellite or the lunar gateway. To ensure prolonged line of sight and enough statistical redundancy for survival, hundreds of ChipSats would be deployed in LLO by one or more CubeSats. The CubeSat would host the ChipSats in a spring-loaded mechanism, which would eject the ChipSats in such a way that they are spin stabilized. Spin stabilization is essential to passively maintain the attitude of the ChipSats, as they lack an active method of attitude control. The CubeSat itself needs to be 3-axis stabilized in order to precisely inject the ChipSats in the right orbit with the right attitude. It will also be equipped with a radio module to allow communication between the ChipSats, the rover on the lunar surface, and the relay satellite. Figure 6.10 below illustrates the mission concept of the ChipSat constellation network for added communication coverage for rover activity on the lunar surface with the Earth orbiting relay satellite or the lunar gateway.

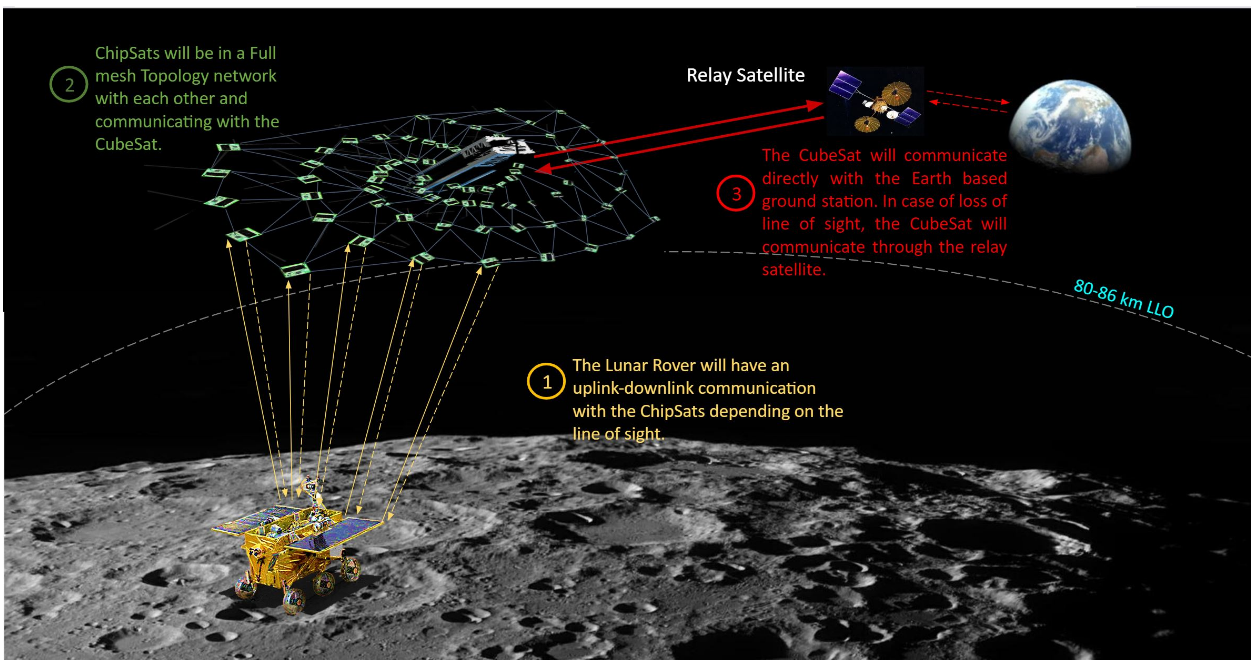

Figure 6.10. Mission design for a ChipSat constellation network for lunar rover communication

The ChipSat design is fairly standard, as it will mainly need only a radio module for networking, a 9 degrees of freedom IMU for attitude determination, a solar panel for power generation, an antenna, and a microcontroller as a processing unit. A small rechargeable battery might also be added for power storage.

In order to ensure full redundancy, the communication network will follow a mesh topology. Whenever there is line of sight between all the nodes of the network (ChipSats, CubeSat, lunar gateway, lunar rover), a full mesh topology (Figure 6.11) will be established so that every node on the network is connected to every other node. While this ensures full redundancy, it is unlikely that all the nodes in the network will be in line of sight with each other at all times, so the network will be dynamic to adapt to a partial mesh topology (Figure 6.11) where necessary.

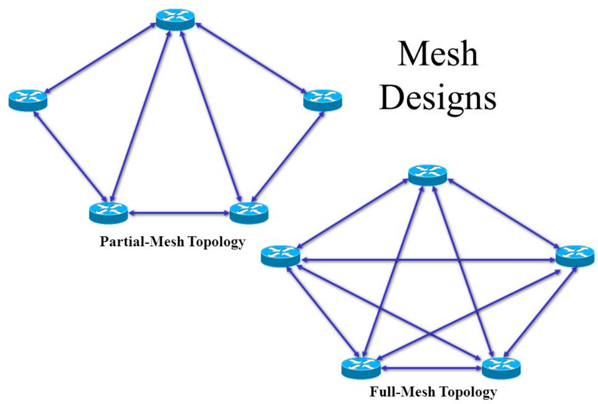

Figure 6.11. Representation of partial and full mesh topology (Profile, 2020)

Deployment spacecraft requirements:

1. 3U CubeSat
2. Capable of storing 128 spin-stabilized ChipSats
3. Deployment mechanism for ChipSats
4. 3-axis stabilization and orientation of approximately eight arcsec accuracy
5. Establish link with Earth orbiting relay satellites or a lunar gateway
6. CubeSat should be capable of receiving a piggyback launch to LLO
7. Delta-V for station keeping in LLO for 12 months and end of life disposal

ChipSats requirements:

1. Radio module to establish link with CubeSat and lunar rover
2. Mesh network topology for decentralized communication
3. 9 DOF IMU for attitude determination
4. Appropriate sensors to fulfill secondary mission objectives (TBD)

As this constellation of ChipSats will act as a backup network, the main payload will be the radio communication components. This mainly includes the radio module and the antenna(s). Such a radio communication component that is capable of mesh networking has been used in the Kicksat-2 mission, hence this component has a TRL of 9. The secondary payload could be temperature sensors, magnetometers, etc, and its choice can be based on its TRL level.

Below is Table 6.6 which explains the various required components for the ChipSats along with their mass and power budgets. The component selection is done and estimations for mass and power has been taken from the previous section on component selection.

Table 6.6. ChipSat subsystems

Component	Mass or Mass/unit area	Power	TRL
Kapton PCB	0.06 g/cm²	0	8
Solar panel : SpectroLab XTJ	0.084 g/cm²	Generated : (32 ± 4) mW / cm²	9

9- axis IMU	0.3 g	Required : 60 mW	6
Radio module CC430 SoC	Unknown	Required : 10 mW	8
Antenna : ANT-LTE-SP610	1.5 g	10 W	>6
OBDH : MSP430 (16-bit)	<1 g	10-20 mW	8
Passive thermal control	N/A	N/A	9

6.2.4 Key Technological Challenges

Challenge 1

An important challenge for this backup network is the survival of the ChipSats in LLO. Far from the Earth's atmosphere, the ChipSats will not be under the protection of the magnetosphere. This will expose the ChipSats to harmful radiation that could potentially, temporarily or permanently damage some of its components. The deployment of a high number of ChipSats will not only allow a large mesh network, but will also ensure a large redundancy. Therefore if some ChipSats that are part of the network suffer from radiation damage, the network will still be operational.

Challenge 2

The ChipSats in the LLO backup network will be powered by photovoltaic cells, and perhaps even a small rechargeable battery. Depending on the orbit in which these ChipSats might be released in, the ChipSats might not be in line of sight of the Sun to power themselves and recharge their batteries. This could cause the ChipSats to run out of power while passing over the subject of interest, for which the signals need to be relayed back to the lunar gateway through the LLO backup network. The presence of a battery can help to reduce such a risk, although ultimately the orbit selection will be the main countermeasure for this challenge. There are several Lithium-ion and polymer-based battery options available which are compatible with ChipSat mass and power requirements. However, they are unable to endure the extremely low temperatures of the space environment.

6.2.5 Commercialization

6.2.5.1 Potential Customers

Lunar Mission Operators

Companies like ispace, OffWorld and Moon Express have planned rover missions to the Moon with the intent to explore, mine and engage in settlements (Hakamada, 2019) and (Howell, 2019). With the Shackleton crater and other untouched craters high on the scientific and commercial priority list, the rovers will be descending into unknown territory. These missions will depend on communication links between the rover and orbiting CubeSats or Gateway, once operational. With line of sight expected to be a concern, deploying a low cost ChipSat swarm can provide a quick and easy-to-execute contingency plan for the communication link.

Autonomous machinery operators like Caterpillar who are leveraging the need for heavy equipment and remote operation feeds to assist in lunar mining and settlement may also have buy-in for this technology, particularly when sensitive equipment is operating in new sectors (Leman, 2019). The high technology transfer potential for these applications makes for a strong financial case and adoption.

Space Agencies

Pursuing an international lunar presence equates to multiple public-private partnerships (PPP) and reliance on commercial market and educational collaborations. Communication remains an ongoing area of exploration with new selections made through the NASA Artemis program supporting university level science and applications. Multiple programs have received funding for research into both ground antennas, power and communication relays and multiple instrument payload development (Damadeo, 2020). The ChipSat communication link can act as a backup while these programs are under development, until they reach readiness levels for launch.

6.2.5.2 Competitors

CubeSats represent a proven workhorse, capable of communication links with rovers, the Lunar Gateway, or Earth. Though a heavier and more expensive choice compared to ChipSats, the current availability regarding both communication and sensor options could tip the scale in their favor, if the mission needs arise before sufficient advances are achieved for ChipSats.

Lunar ground-based antennas are in development through the NASA Artemis student challenge program. MIT is currently developing an unfolding antenna designed for robust communication with rovers. This alternative could render the ChipSat communication deployment redundant (Damadeo, 2020).

Collaborative rover pairs are similarly under development through multiple university, commercial and space agency projects such as the TRAILER project displayed in Figure 6.12. These are pairs of rovers that work in tandem, with one acting as a communication link or relay for a second more mobile platform. Many scenarios include provisions for added power distribution or recharging options, which is highly attractive for extended exploration missions (Weiss, 2019).

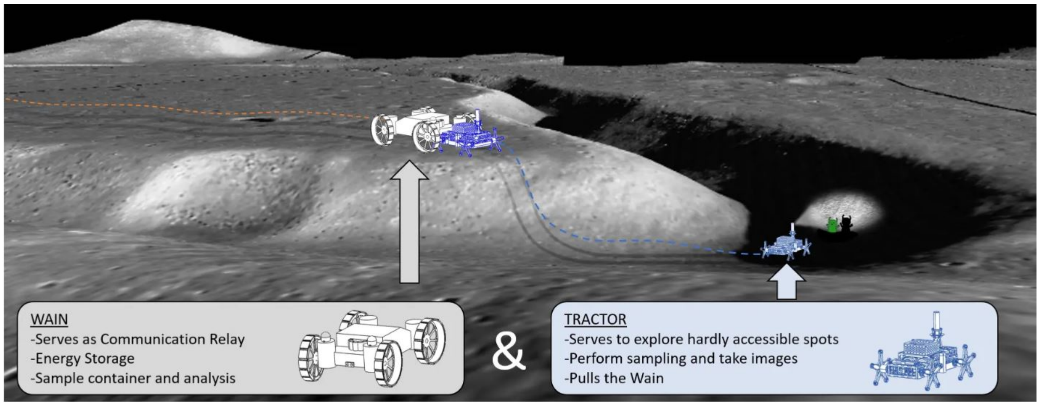

Figure 6.12. System components of the TRAILER project (Weiss, 2019)

6.2.5.3 Revenue Streams

Mission-specific deployments and instrumentation bring benefits to the commercial enterprises establishing mining and construction presences. The ChipSats can be leased to the commercial operation for a specified time period (one month before planned deorbit), and charged for the space debris recovery associated with the deorbit plans.

Science grants or collaboration with other citizen science programs may result in sponsorship opportunities. The Great Lunar Expedition for Everyone (GLEE) project is pursuing educational outreach and science relating to lunar ChipSat missions called LunaSats (Hebden, 2019). This is a STEM engagement program that dovetails nicely with the ISU Roadmap and offers a chance to engage with their platform and provide parallel programming.

6.2.5.4 Cost Estimate for Mission

The following items were considered as part of an initial cost profile:

ChipSat cost (128 units)

An AmbaSat kit is proposed at the cost of $280 (AmbaSat, 2019). Being a kit, both integration and production costs need to be estimated. A single eight hour work day is sufficient for integration and testing. Assuming eight hours/day at a rate of $20/hour = $160, bringing the total cost per ChipSat (AmbaSat) to $440.

Note: In this model, we assume that the AmbaSat kit will have all the components required for this mission, therefore we do not include development costs.

3U CubeSat cost (1 unit)

According to Alén Space's Basic Guide to Nanosatellites, the entire cost of building and placing a nanosatellite in orbit can be done for less than €500,000 (Alén Space, 2020), or around $567,000. We will assume that this price is built from 70% development efforts, 20% production and 10% launch costs.

Hence, the NRE cost for this mission will be $350,000 and the RE cost of the CubeSat including its launch will be $150,000.

Communication segment (128 units)

A mesh network topology will be used for radio communication. Each ChipSat will be fitted with an Arduino-Based LoRa RFM95 radio transceiver. The network topology allows LoRa nodes to communicate either directly (if in range) or indirectly via an intermediate node (CubeSat). There is no additional cost as the unit is supplied with the AmbaSat kit. Total costs for this Mission are shown below in Tables 6.7 and 6.8:

<u>Model 1: One CubeSat, 128 ChipSats</u>

Table 6.7. Lunar Mission Total Cost of Model 1

Item	QTY	Cost	Comments
CubeSat NRE costs.	1	$350,000	$350,000 each
CubeSat + 128 ChipSats: production + launch costs.	1	$194,000	$194,000 each
Communication transceiver*.	128	TBD	TBD*
Labor (management, procurement, legal): 12 months.	2	$120,000	$30 per hour
Sub Total:		$664,000	
G&A, miscellaneous, unexpected: 30%.		$199,200	
Insurance:In-orbit 0.60%, Third party 0.075%.		$4,482	
Profits: 15%.		$99,600	
Total costs:		**$ 967,282**	

*Cost of a transceiver for future use in the mesh topology is not currently available. For the Mission costs we are assuming the included Arduino Transceiver shipped with the AmbaSat.

<u>Model 2: Two CubeSats, 256 ChipSats</u>

Table 6.8. Lunar Mission Total Cost of Model 2

Item	QTY	Cost	Comments
CubeSat NRE costs.	1	$350,000	
CubeSat + 100 ChipSats: production + launch costs.	2	$388,000	$194,000 each
Communication transceiver*.	256	TBD	TBD*
Labor (management, procurement, legal): 12 months.	2	$120,000	$30 per hour
Sub Total:		$858,000	
G&A, miscellaneous, unexpected: 30%.		$257,400	
Insurance: In-orbit 0.60%, Third party 0.075%.		$5,792	

Profits 15%.		$128,700	
Total costs:		**$1,249,892**	

*Cost of a transceiver for future use in the mesh topology is not currently available. For the mission costs we are assuming the included Arduino Transceiver shipped with the AmbaSat

6.2.5.5 Key Mission Risks and Assumptions

The major mission risks that may compromise mission quality or prevent mission success were considered and are outlined below. Table 6.9 outlines the consequence criteria, Figures 6.13 and 6.14 look at the risk likelihood to consequence matrix before and after mitigation strategies are implemented. Table 6.10 displays the mitigation required for all risks above a determined allowable risk threshold (3C). All tables were prepared in accordance with ESA's Scientific Directorate Risk Management guidelines, as well as appropriate risk mitigation strategies (Schroeter, 2001).

R1 - TRL

Many of the scientific missions are hypothesized and require steep advancements in TRL, particularly in the miniaturization (MNT) of sensors. Following the evolution of the CubeSat from an educational outreach platform to one which is capable of performing complex and highly detailed scientific missions, we are making a certain level of assumptions regarding the ChipSat development to follow suit.

R2 - Introduction of alternate communication relays

The NASA Artemis Student Challenge has recently tasked universities in the US with developing rovers and ground-based antenna towers to assist with providing communications relay to machinery exploring deep craters below the lunar surface. However, the cost and development cycle could prove to give the ChipSats a distinct advantage (Damadeo, 2020).

R3 - ChipSat Survival

It is assumed that ChipSats will be able to survive in the harsh LLO environment for at least one year. If this is not the case, the mission duration may be cut short, compromising main mission objectives.

R4 - Deployment Failure

The possibility exists for deployment failures, as seen in the KickSat launch of 2014. A deployment failure for a single CubeSat would result in a complete mission failure, hence a double CubeSat mission deployment is advisable. The failure could be the result of either a communication problem or a mechanical operation.

R5 - Space debris mitigation for deorbited ChipSats

The Moon Treaty Article 7.1 limits the introduction of foreign material on the surface, so a clear collection plan must be included in the mission planning. The current method proposed for attitude adjustments of the ChipSats involves active magnetic attitude control. However, deorbiting the ChipSats will require some level of propulsion, which is not an option utilizing current technology.

R6 - Communication Loss

There is a possibility of failure for the CubeSat communication subsystem, which tends to be one of the common failures among CubeSat missions in general. In this case, there will be a communication link disconnect between the ChipSats and Earth-based ground stations.

R7 - In-Orbit Collision

Collisions between ChipSats and another spacecraft could lead to a Kessler event, taking out all spacecraft in the LLO orbit. ChipSats are difficult to track due their small size, and lacking propulsion could lead to a stray spacecraft capable of wiping out the ChipSat cluster, the CubeSat relay, including other satellites or spacecraft in the orbit.

R8 - Space Weather

A strong enough EM event could result in the loss of the CubeSat communication link but will more likely result in the full loss of the ChipSat network. The CubeSat will have been rigorously tested to withstand the LLO environment and may possess a better ability to prevent a total loss of electronic subsystems. Due to the high numbers (128 per CubeSat) to be deployed, redundancy could assist in preventing a total mission loss.

R9 - Incorrect Orbit Deployment

A malfunction in the deployment could place the ChipSats into an incorrect orbit. Without propulsion, this would render the mission obsolete as ChipSats cannot perform delta-v maneuvers to adjust position.

R10 - ChipSat components or systems failure

The possibility of ChipSat EEE COTS component or systems failure must be taken into consideration.

Table 6.9. Consequence Criteria for Risk (Modified from Brumbaugh and Lightsey, 2012)

Level	Technical	Schedule	Schedule Impact to Mission	Cost	Cost Impact to Mission
1	Minimal or no consequence to technical performance	Minimal or no impact	No change	Minimal or no impact	No change
2	Minor reduction in technical performance, can be tolerated with limited impact on program objectives	Able to meet key dates	Slip <1 month	Budget increase or unit production cost increases (1% of budget)	Increase <$10k

3	Moderate reduction in technical performance with limited impact on program objectives.	Minor schedule slip. Able to meet key milestones.	Slip <3 months	Budget increase or unit production cost increases (5% of budget).	Increase <$30k
4	Significant degradation in technical performance. May jeopardize program success	Program critical path affected	Slip <6 months	Budget increase or unit production increase (10% of budget)	Increase <$50k
5	Severe degradation in technical performance, cannot meet key technical threshold; will jeopardize program success	Cannot meet key program milestones	Slip >6 months	Exceeds budget threshold (10% of budget)	Increase >$50k

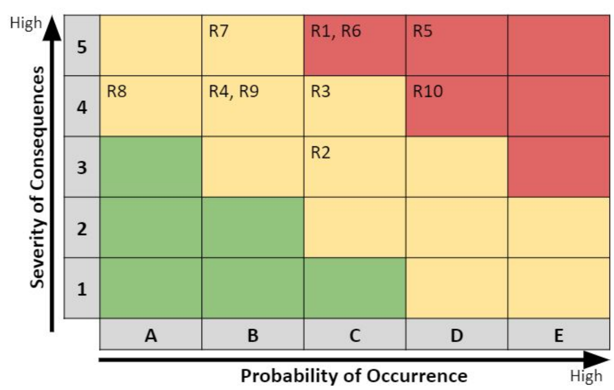

Figure 6.13. Lunar communication and Science mission risk matrix displaying levels of various risks before mitigation

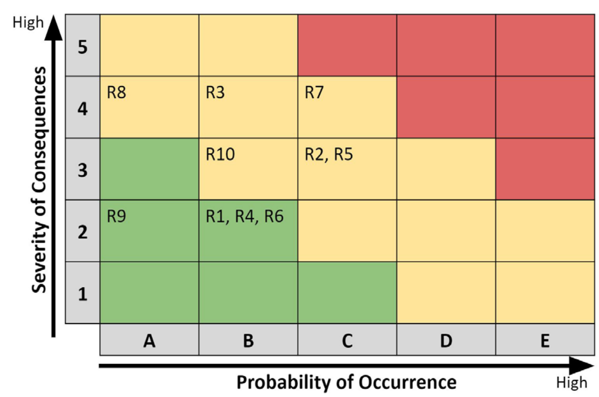

Figure 6.14. Lunar communication and science mission risk matrix displaying levels of various risks after mitigation

Table 6.10. Lunar communication and science mission risk mitigation strategies

Risk	Control Measures
R1	Acceptable Risk
R2	Acceptable risk
R3	1. Increase redundancy by deploying a large number of ChipSats 2. Conduct robust radiation testing of ChipSat critical components
R4	Acceptable risk
R5	Acceptable risk
R6	Acceptable risk
R7	Developing propulsion for the ChipSats would reduce the likelihood of in-orbit collisions Developing a tracking system for very small satellites would also help to mitigate this risk
R8	At this time, there are no known mitigation strategies for avoiding space weather. A direct hit could end the mission

R9	Acceptable risk
R10	Acceptable risk

6.2.6 Legal Implications

The legal implications of the lunar science mission are similar to those presented for the space weather mission in Chapter 6.1. However due to the mission architecture and location, there are some additional considerations to be addressed and these are discussed in the following pages.

6.2.6.1 Space Debris

This primary international policy hindrance with the lunar mission is the lack of agreement on conduct on celestial bodies and on-going governance. The only international agreement directly concerned with activities on celestial bodies is the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, better known as the the Moon Treaty, created in 1979.

In Article 7.1, the treaty states: “In exploring and using the moon, States Parties shall take measures to prevent the disruption of the existing balance of its environment, whether by introducing adverse changes in that environment, by its harmful contamination through the introduction of extra-environmental matter or otherwise” (UNOOSA.b., 1979).

Unfortunately the Moon Treaty is largely ornamental; it has been ratified by less than one dozen States. In its opposition, States have introduced their own national laws concerning appropriate conduct on the Moon, including the US Commercial Space Launch Competitiveness Act of 2015 (Congress.gov, 2015), and Luxembourg’s framework for The Exploration and Use of Space Resources of 2017 (Luxembourg Space Agency, 2017).

These new frameworks enable commercial exploitation of lunar resources, but do not address the end-of-life procedures or debris mitigation created as a result of lunar missions. Thus, at this time, there is no legal framework for space debris with regards to the Moon. The need for an international regime to govern operators is of particular importance with this lunar mission as the secondary mission objectives in Section 6.2.2.1 propose deorbiting ChipSats onto the lunar surface in an end-of-life, suicide mission.

Core elements of a space debris and mitigation plan on the lunar surface must include the considerations outlined in Table 6.11 and Table 6.12 below.

Table 6.11. Element 1: Definitions of Space and Celestial Debris

Primary objective: Temporary deployable LLO ChipSat network	**Secondary Objective: Sensory data from within lunar craters**
A clear definition of what constitutes as **“space debris”** in the scope of lunar missions. This definition must be binding, but not restrictive, to enable State, inter-State, and commercial actors to mitigate space debris The current definition of space debris only considers man-made objects within Earth’s orbit. The Moon is a separate celestial body beyond Earth’s Graveyard Orbit found at 36,000 km above the surface of the planet,	

which does not have any mitigation in place for debris resulting from space operations. Thus, a strategy for "**celestial debris**" must be developed

Table 6.12. Element 2: End-of-life procedure.

ChipSat Deployer	**ChipSats**
Debris mitigation: (1) Active deorbiting, (2) Graveyard orbit, (3) Inspace retrieval	Debris mitigation: (4) natural decay of ChipSat orbit
Active Deorbiting of ChipSat deployer The CubeSat which deploys the ChipSats is unlikely to disintegrate upon re-entry due to the insufficient lunar atmosphere. A strategy must be in place for guided deorbit and on surface retrieval	**Natural decay of ChipSat orbit** The lack of propulsion control on ChipSats leads to natural decay of the orbit the only option for end of life procedure
Ejection of ChipSat deployer into an external orbit determining which graveyard orbit ChipSats should occupy at EOL	
Inspace retrieval of ChipSat Deployer active removal of the ChipSat deployer while it is still in orbit. Infeasible due to low TRLs and cost	

In terms of a framework for the sustainability of lunar missions, special consideration must be given to the natural decay of the ChipSat orbit. Once ChipSats are released by the deployer, no corrections or modification can be made to their path. With the secondary mission objective of deorbiting ChipSats onto the lunar surface, and potential of future ChipSat missions to support the Lunar Gateway operations, the impact on other space assets in the ChipSat's path is required. A single mission deploys hundreds of ChipSats, therefore it is crucial to develop a strategy to enable casualty-free natural orbit decay and post-impact clean up.

6.2.6.2 Cybersecurity

Encryption for the lunar mission will be even more critical as the communication relay provided by the temporary deployable LLO ChipSat network will be susceptible to cyber attacks. Current small satellite developers rely on open-source OS, which serve as an entry point to more complex networks including lunar rovers, spacecrafts, the mother satellite for the ChipSat network, etc. Small satellites generally use unencrypted Telemetry, Tracking, and Command (TTC) or mission data communication links as it allows them to achieve a faster time-to-market at a lower cost.

7. Discussion

The primary mission of the overall TP was to extensively explore the existing and future opportunities for ChipSats and establish an ISU Roadmap to leverage these opportunities. This has been admirably met through the hard work and dedication of the entire team. A strong emphasis on inspiring the space community and encouraging a sustainable relationship between humanity and space exploration can be seen throughout the report. Within a team composed of 18 different nationalities and a variety of technical and non-technical backgrounds, there were many challenges along the way in terms of maintaining healthy team dynamics while tackling a relatively new and unexplored topic of ChipSats. However, through mutual respect, professionalism and participation in exciting team bonding activities, the team was able to adequately surmount these challenges. Accomplishing the secondary mission of this TP emphasized the importance of team building and envisioning the future of ChipSats in a sustainable light. In fact, although the unexplored nature of ChipSats made the overall project quite challenging, it left great room for creativity which is extensively visible in the ISU Roadmap and future mission concepts development.

The miniaturization trend has resulted in a paradigm shift from conventional satellite design of high development expenditure, time, and complex engineering to faster, better, and cheaper disruptive technologies as seen with the advent of ChipSats. As summarized in Table 7.1, the Literature Review for this project revealed the key strengths, weakness, opportunities and threats of and for ChipSat technology. However, there will still many questions left unanswered.

Table 7.1. ChipSat SWOT Analysis

Strengths: Massive cost reduction Lower entry barriers for space technology Accessibility and rapid development Redundancy due to quantity Design modularity	**Weaknesses:** Lack of regulation Launch opportunity restrictions Low functionality Space debris Orbit lifetime
Opportunities: Distributed system Innovation Lowering ground segment dependency Ability for new scientific missions and new applications for social economy	**Threats:** Policy restrictions Misuse Debris damages Loss of satellite Unproven business cases

This report sought out to answer the fundamental question: Will this “faster, better, cheaper” ChipSat technology be capable of exhibiting promising potential and achieving mission critical objectives? Based on the extensive research, critical analysis, and informative new ideas displayed throughout the report, three underlying themes can be established to answer the above question.

1. There is future potential for ChipSats as a pragmatic space technology. The low development costs, mass production capabilities, and unprecedented levels of redundancy invite innovative space mission concepts and applications. It is not the technology itself but the exceptional manner of conducting missions that give ChipSats the competitive edge compared to existing technologies. High risk missions and distributed systems such as distributed sensor systems seen in the case of the Space Weather Mission, or distributed communication systems seen in the case of the Lunar Communications Mission, seem to be the most prominent future applications of this technology primarily due to the high degree of redundancy. ChipSats have indeed proven to be a disruptive technology by distinctly lowering the entry barrier and consequently increasing accessibility allowing

new players to enter the space domain. The effective broadening of access to the wider community is a result of the low cost, low depth of required expertise and high design modularity

2. There exist factors and gaps that present themselves as impediments to the future opportunities of ChipSats. The future evolution of ChipSats is consistently compared to the recent evolution of CubeSats, however in order to follow a similar trajectory, ChipSats must overcome some fundamental legal and technological challenges

   i. First and foremost, there is no fundamental and universally accepted definition of ChipSats, as legislation that typically defines requirements and guidelines for satellites does not exist for this unique category of small satellites. As a result, ChipSats will continue to be portrayed as belonging to a high-risk category and be cautiously approached by the commercial space sector and educational institutes. Lack of tailored legislation also makes bureaucratic tasks such as insurance fees and technical requirements more challenging to prove in order to obtain appropriate licensing for launch

   ii. The lack of policies surrounding the topic of space debris impose further barriers to obtaining essential clearances and licenses for launch due to the existence of many uncertainties. Imposing such policies and regulations however can be a double-edged sword as excessive restrictions have the potential of hindering the growth of the ChipSat market

   iii. The technological challenges associated with space debris mitigation require solutions to allow the maturation of the ChipSat market. To a great degree, this issue revolves around the lack of propulsion and control associated with these small satellites. There is currently no viable solution for this gap. Nevertheless, it is essential for it to be addressed in order to demonstrate the viability and utility of future Earth-based ChipSat applications

   iv. There exist other payload and TRL-related subsystem capability limitations due to the volume and mass restrictions of ChipSats. More specifically, there are currently no means for power storage onboard a ChipSat at an acceptable TRL level, and the effectiveness of solar cells as the lone source of power is further limited by the lack of propulsion for attitude control. Thermal control is another major limitation for ChipSats which also influences power storing capabilities. Finally, the communication capabilities are extremely limited in terms of bandwidth due to power limitations

3. There is current potential for ChipSats which ISU should leverage. A majority of current ChipSat applications can be found in the citizen space sector, which includes educational institutions and other non-profit programs. ISU can benefit from taking a step towards achieving its Institutional Objectives by leveraging ChipSat technology for educational and scientific purposes. Following the path of knowledge and skills acquisition, community outreach, and ISU technology development, ChipSats provide a means by which ISU can strengthen its identity as a global leader in space education by fostering deeper connections with its educational and industrial partners, as well as underrepresented nations. The low development time, low cost, and low barriers to entry of ChipSats make them an ideal candidate for educational and outreach events. Moreover, developing ISU's

capabilities of creating and launching its own ChipSat missions can lead to new opportunities for cooperation within the space sector, as well as advancing and developing the next generation of ChipSats through R&D pertaining to the technological gaps mentioned previously

8. Recommendations

The work performed in this project reviewed, analyzed and discussed numerous aspects of ChipSats. Action items for future activities have been put forward by the ISU Roadmap, Space Weather and Lunar Communication Missions chapters. This recommendation chapter extracts and focuses on the most critical action items proposed, and has been supplemented by a set of high-level recommendations for industry to consider.

It is our understanding that addressing and implementing these recommendations will be fundamental to driving the maturity of ChipSat technology which can potentially unlock new missions.

Taking the technology analysis performed in Chapter 3 into consideration, the team recommends both industry and ISU tackle the identified technology gaps by developing solutions contained in the following Table 8.1, 8.2, 8.3, 8.4, 8.5, and 8.6. It should be noted that the expansion of ISU's capability regarding ChipSats has also been addressed by proposed Individual Projects and MSS Assignment within Section 5.9.

1. Technology and Engineering

Table 8.1. Technology and Engineering-related recommendations

Topic	Recommendation	Who should address this recommendation
Thermal Control	Develop technology that will expand the existing optimal working temperatures or facilitate thermal regulation on ChipSats	Technology industry Potential ISU IP
Power Storage	Develop power storage capabilities within the physical (i.e. size and mass) boundaries of a ChipSat and thermal constraints of space	Technology industry Potential ISU IP
Attitude Control	Develop three-axis attitude control technology compliant with the required physical properties (i.e. size and mass) and expected power budget of a ChipSat	Technology industry Potential ISU IP
ChipSat Location Determination	Develop a systematic solution for identifying and logging the location of the ChipSat at any time (e.g. when making a sensor sampling) within the required location accuracy	Technology industry Potential ISU IP

Note: The list is prioritized according to the technology gap dependencies

2. Legal

Table 8.2. Legal recommendations

Topic	Recommendation	Who should address this recommendation
Supervising Legal Activities	Assign the ChipSat program a legal expert who will supervise all legal activities on ChipSat development, production, launch, and operation as a miniature space object. Knowledge required for the current small satellite legislation landscape	ISU ChipSat program Any company that plans to launch a ChipSat of its own
Obtain Licenses	Start the application procedures for frequency allocation and licensing, taking an 18 to 24 month lead time	ISU ChipSat program Any company that plans to launch a ChipSat of its own
Export Control	Avoid using any export-controlled component for the ChipSat if possible	ISU ChipSat program Any company that plans to launch a ChipSat of its own
Space Debris	Mitigate and comply with the set space debris guidelines (IADC)	ISU ChipSat program Any company that plans to launch a ChipSat of its own

3. ISU ChipSat Program

Table 8.3. ISU ChipSat Program recommendations

Topic	Recommendation	Who should address this recommendation
Organization	Implement an organization structure and a steering committee for program decision-making	ISU ChipSat program office
Finance	Assess annual expenses, allocate budgets from internal resources, and apply for R&D grants	ISU ChipSat program office
Academic	Assign an academic manager who will develop the learning curriculum and will supervise skills development, pre-requisites, etc	ISU ChipSat program office
Outreach	Make the first pilot in the 2021 academic year, assess lessons learned and establish an annual program for 2022 onwards	ISU ChipSat program office

4. Lunar Mission

Table 8.4. Lunar mission recommendations.

Topic	Recommendation	Who should address this recommendation
Sensors	Work with sensor manufacturers (in radiation and seismograph) to miniaturize technology further, until ChipSat platform compatible	Technology industry Potential ISU IP
Communication Transmitters	Enhance miniaturized transmitter output power levels to boost communication capabilities	Technology industry Potential ISU IP
ChipSat Relay Network	Work with alternate communication development (antenna and rover) to assess backup communication links	Technology industry Potential ISU IP
Debris Mitigation Plans for Commercial Markets	Create value proposition for mining exploration companies and autonomous machinery operators to develop debris mitigation payment and cleanup plans	Technology industry and law Potential ISU IP

5. Space Weather Mission

Table 8.5. Space weather mission recommendations

Topic	Recommendation	Who should address this recommendation
Magnetometer Accuracy	Develop a viable shielding strategy to defend against electromagnetic interference for the magnetometer from other ChipSat subsystems	Technology industry Potential ISU IP
New Sensors	Develop new types of sensors which can sense space weather phenomena; plasma, electromagnetics, and radiation levels	Technology industry Potential ISU IP
Assess Market Needs	Conduct a detailed market analysis to verify the need for space weather data related to the Earth's magnetic field	Space industry Potential ISU IP

6. Other industry-related recommendations

Table 8.6. Industry-related recommendations

Topic	Recommendation	Who should address this

		recommendation
Development Standardization	Establish a ChipSats standardization work group involving the relevant developers and manufacturers	ISU may want to lead this effort
Minimizing Debris	Address mandatory guidelines for ChipSat end of life, which will minimize creation of additional space debris by ChipSat missions	United Nation office for outer space affairs ISU may want to lead this effort

9. Conclusions

Since the launch of the world's first satellite in 1957 with Sputnik-1, the space industry has transformed the way humans communicate, navigate, and view the world. The progressive downsizing of satellites in the last six decades has resulted in an expansion of the space industry impacting economic growth in many sectors. Current use of satellite technology impacts crucial navigation systems, transportation solutions, health monitoring, and many others. Miniaturization, the emergence of constellations, and a reduction in technical barriers and the cost to launch have opened the doors to non-traditional actors.

This report has made the case for the next generation of small satellites, ChipSats, by expanding upon the multidisciplinary benefits of this technology; from an education and outreach perspective to planetary atmospheric research. After considering the potential near and distant future applications of ChipSats, the team chose the three most feasible missions based on a combination of commercial, scientific value, and engineering practicality, and investigated the value of these missions in depth.

The first mission, the ISU outreach campaign, is a roadmap for ISU to achieve the following institutional goals: (1) enhancing education, (2) increasing diverse enrollment, (3) economic stability, (4) growth for future MSS cohorts, (5) promotion of ISU's 3Is principles, and (6) efficient utilization of resources and talent. This ChipSat mission will complement the MSS curriculum and provide students with relevant hands-on experience in a long-term project. Students will understand the lifecycle process of creating and launching their payload, and be familiarized with all phases of a spacecraft mission, including developing systems requirements and specifications, hardware and software design, integration and implementation, verification and validation, deployment of payload, and end-of-life operations. Current ISU facilities Make-It-Space and Payload Lab will be modified and expanded to meet this objective, while inter-institutional corporations will fulfill other facility needs.

The outcome of this mission is the democratization of space and raising awareness of the potential of ChipSats on an international scale. During the five year lifespan of the ISU Roadmap, high school and university students studying space will be engaged in a global outreach campaign. This effort will promote inclusivity by encouraging students and educators from underrepresented nations in the space sector to take part.

Per the proposed design, students will plan their mission and build their satellite using pre-assembled ChipSat kits to become familiar with the interdisciplinary nature of space missions. At an affordable price, the kit provides students with an opportunity to study the atmospheric quality of their present environment, including UV radiation, radio transmission capability, temperature, humidity, pressure, and the existence of volatile compounds, etc. using ChipSats. The kit demonstrates the off-the-shelf potential of SmallSats and the increasing ease of access to space while providing hands-on training in an educational setting. This experience encourages students to work and think about furthering their careers in the space sector, through institutional collaborations and partnerships with ISU.

The second mission considers the benefits that ChipSats pose for Earth through space weather monitoring. Currently, the lack of accuracy in space weather data has a significant economic cost in on-ground and space-based technologies. The space weather mission launches hundreds of ChipSats into LEO, allowing accurate data collection and distribution of Earth's environmental conditions. The variety, quantity, and accuracy of the data collected enable us to calibrate the models of space weather forecasting for a better understanding of our planet, and better precision in space weather forecasting.

The third mission considers the value of ChipSats as an asset in interplanetary space communication, specifically focusing on the near-future missions to the Moon. With the deployment of the Lunar Gateway in 2024, there is an urgent need for communication capabilities, both on the lunar surface and with Earth. The deployment of a ChipSat swarm in out-of-sight or difficult to access regions provide a temporary solution for further development of the Artemis mission. A constellation can collect data regarding lunar environmental conditions throughout its lifetime and upon deorbit. We can investigate regions including craters and lava tubes, before assigning human missions to a given location.

The prospective uses of ChipSats, both on Earth and in space, touch upon many facets of human life and our growing reliance on space architecture. A swarm of ChipSats provides a unique solution that large satellites cannot. Combined with their compatibility with other emerging technologies such as solar and laser sails plus EDTs, ChipSats are well-suited for the future ahead. Their future will rely on easily fabricated and multi-use systems, rather than single-purpose and single-use technology. As stated in the beginning of this report, satellite health monitoring, space debris tracking, biological research, and planetary atmospheric studies are just some of the future possibilities with ChipSats. With the continued research and use of this technology, we can expect the breadth of applications to widen. Unlike traditional satellite systems, the small size and short lifespan of ChipSats take into consideration the ever-growing problem with space debris in LEO and provide a more sustainable alternative. In conclusion, ChipSats offer a low-risk, low-cost option to all interested in technologies benefiting humanity.

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