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Investigations on the current and future use of radio frequency allocations for small satellite operations

Universitätsverlag der TU Berlin

Technische Universität Berlin

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E-Mail: publikationen@ub.tu-berlin.de

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Abstract

Global radio frequency spectrum use for satellite communication is a present-day challenge that has been aggravated by the increased launch of small satellites during the past 15 years. This thesis aims to examine both regulatory and technical aspects of spectrum use. The focus of this examination is on frequency bands that are commonly used by small satellites and on those bands that might be applicable for future use. The thesis content is subdivided into three parts. The first part presents the needed background on small satellites as well as the regulatory environment for small satellites. The second part gives insight into the results of a theoretical assessment of current and future small satellite allocations. The third part depicts two concepts for on-orbit spectrum analysis applications which allow the analysis of the problem from the technical side, including first flight results.

After studying this work, the reader shall be able to understand regulatory procedures for frequency coordination and to acknowledge challenges for both satellite developers and responsible administrations. The presented hardware implementations for spectrum analysis shall serve as a tool for improved frequency coordination in the near future.

Zusammenfassung

Durch die steigende Anzahl von Kleinstsatellitenstarts in den letzten 15 Jahren ist auch die Auslastung vom für die Satellitenkommunikation verfübaren Funkspektrum signifikant gestiegen. Während die ersten Kleinstsatelliten (CubeSats) aufgrund ihrer Neuheit und ihrer kurzen Lebenszeit von regulatorischer Seite unbeachtet blieben, stiegen in den letzten Jahren Interferenzfälle sowie die Frage, wie Kleinstsatelliten regulatorisch behandelt werden sollen. Diese Arbeit betrachtet die aktuelle und zukünftige Nutzung vom für Kleinsatelliten verfügbaren Funkspektrum aus regulatorischer und technischer Sicht. Der erste Teil der Arbeit behandelt die regulatorischen Rahmenbedingungen von Kleinstsatelliten und bietet einen Einblick in das Themengebiet Frequenzkoordinierung. Der zweite Teil untersucht Möglichkeiten zur verbesserten Frequenzkoordinierung im Rahmen von ITU-Studien. Im dritten Teil der Arbeit wird die technische Implementierung von Weltraumanwendungen zur Spektrumanalyse präsentiert. Flugergebnisse eines Spektrumanalysator sowie eine Satellitennutzlast zur Spektrumanalyse werden vorgestellt.

Durch die Lektüre dieser Arbeit soll eine Einführung in die Frequenzkoordinierung von Kleinstsatelliten gegeben werden. Aktuelle Entwicklungen auf regulatorischer Seite sowie aktuelle und zukünftige Ergebnisse der Spektrumanalyse aus dem Orbit werden als Hilfsmittel für Koordinierungsvorgänge vorgestellt.

Contents

List of Figures

List of Tables

1 Introduction

"Members shall endeavour to limit the number of frequencies and the spectrum used to the minimum essential to provide in a satisfactory manner the necessary services." (ITU Radio Regulations, Article 0.2)

The available frequency spectrum for RF applications is a scarce resource. Various services, both terrestrial and space-based, aim to share this resource as efficiently as possible. Since more and more satellites are launched into space, the coordination of incumbent and new users becomes increasingly difficult. This work deals with the integration of small satellites into the existing frequency coordination environment.

1.1 CubeSats: A new class of satellites

With the invention of the CubeSat Design Specifications (CDS) [1] in the beginning of this century, a new class of satellites was created. While the term small satellites earlier used to define satellites with a mass of less than approximately 500 kg, this term nowadays most often refers to satellites whose mass is at least one tenth smaller. Since the development and launch cost as well as the development time are mainly driven by the mass and dimensions of the satellite platform, the possibility to conduct missions on smaller platforms is tempting and increasingly often adopted by satellite developers.

The success of (very) small satellites is mainly based on two reasons: The first reason is the miniaturization of components and equipment. Miniaturization and the use of highly integrated circuits allow a major reduction of the system's dimensions. Traditional systems need larger platforms purely for design reasons, e.g. analog circuits, traveling wave tubes or power electronics. Cubesats can integrate several subsystems on one printed circuit board (PCB) board, as shown in [2]. The second reason is the establishment of the CDS standard by Twiggs et al. that was accepted by a fast growing community. CubeSats are defined by their form factor: a 1U CubeSat has an edge length of 10 cm x 10 cm x 10 cm. A 2U CubeSat has 20 cm x 10 cm x 10 cm. Based on this concept, there are versions with bigger and smaller dimensions, e.g. 3U, 6U, 12U and 27U, and even 0.25U. The

CDS standardized the dimensions of various subsystems as well as the deployment mechanisms in the form of deployment containers. Integrating satellites into standardized containers has the benefit that launch system providers can more easily integrate so-called "piggy-back" satellites when the main rocket payload does not utilize the rocket's full mass capacity. This reduces the launch cost for the primary payload developer and offers low-cost launches for Cubesat developers. Standardized containers optimize the integration density and ease the pre-launch calculation of physical rocket parameters (center of gravity, moment of inertia, ...). Additionally, in case that a small satellite developer cannot complete the manufacturing and delivery of the satellite in time for a launch, it is comparably easy to replace the satellite with another CubeSat that seeks a launch opportunity. This maximizes the effective use of launch opportunities.

First developers and users of CubeSats were universities. These early adopters used the new standard for educational purposes and for technology demonstration. Since the complexity of CubeSats can be comparatively low, the standard allows the design, development and manufacturing of structures and subsystems in short cycles. Although the development time can be longer when the complexity of the payloads is high, even newcomers can develop a CubeSat in a period of few years. Due to the short development time, it became possible to design (sub)systems as part of lecture courses and raise the experience that students would gain to a new level. At the same time, research projects at universities were initiated that added scientific applications and guaranteed the funding of the project and launch costs. Governmental institutes and financial supporters of universities (mainly space agencies, e.g. NASA, DLR, ESA, ...) saw the potential and benefit of CubeSat projects and offer various programs even for new entrants to satellite development.

Early systems mainly focused on the general demonstration and qualification of (highly-integrated) technology in space. After the first successes in space, universities and research institutes integrated more systems on smaller dimensions, tested new miniaturized components and with that moved to more complex systems. As the systems became more mature, alumni of universities and institutes recognized a potential market in the commercial application of small satellite technology. First companies and university spin-offs were founded (ISIS, Pumpkin Inc., GOMSpace, ClydeSpace, ECM, . . .) that offer CubeSat structures, components, launches and more.

Early developers used commercial off-the-shelf equipment, e.g. transceivers, microprocessor circuits, solar cells and mechanisms. Today, complete satellite buses can be bought off-the-shelf. This development along with more reliable implementations opened the technology for commercial applications, most often Earth observation missions. After the first wave of newcomers stagnated around 2013-2015, the adoption of CubeSats as a commercial platform raised the number of launches to a new level that will even climb higher, as presented in the next chapter.

1.2 Small satellite launch development

The first revision of the CubeSat design specification was released in 1999. The first CubeSat launch took place in 2003. Following this, only few launches were registered until 2009. During this early period, more and more universities started their CubeSat research and development until a recognizable number of systems were designed and launched between 2009 and 2012. At Technische Universität Berlin, the first CubeSat was launched in 2009 after preceding projects focused on the development of miniaturized CubeSat components. Following the very successful operations of the first Berlin Experimental and Educational Satellite (BEESAT) [3], various follow-up projects were initiated [4, 5]. Naturally, the same happened at other universities. After the first successful (and admittedly some unsuccessful) launches, developers started to build and launch their second and third generation of CubeSats. Along with the entry of new developers, the number of launches significantly raised around 2013. While the first CubeSats were developed in the more experienced space-faring countries (USA, Canada, Germany, Japan, ...), new entrants emerged even from countries that never launched a satellite before their first CubeSat.

Figure 1.1 shows the number of CubeSat launches from 2003 until 2017. The trends explained above are clearly visible. After the first years of cautious increase, starting from 2012/2013 the establishment of CubeSats as a serious competitor for traditional satellites is unmistakable. Starting from 2017 the deployment of commercial systems and constellations added to the constantly rising number of launches. Several forecasts [6, 7, 8, 9] project that in the upcoming years the annual number of launches will be well beyond hundreds. This poses a problem to the efficient and interference-free satellite communication channels, which shall be explained in the next chapter.

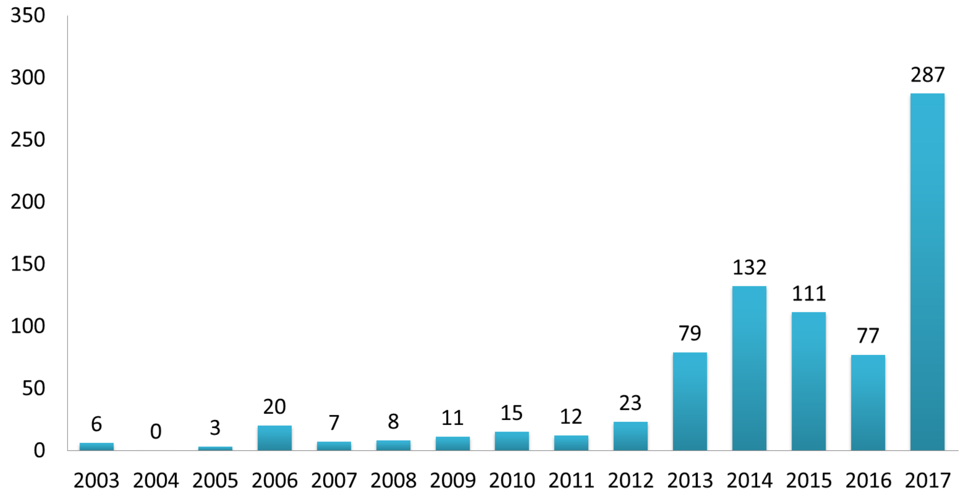

Figure 1.1: Number of CubeSat launches (adapted from [6])

1.3 Current practice in filing satellites

Each satellites needs designated RF spectrum for its communication. This communication is either between Earth and satellites, e.g. uplink and downlink, or between two or more satellites (inter-satellite link). Space applications that use RF spectrum are vast: Broadcast (TV, radio), communication systems (satellite phones, safety and rescue systems), active sensors (e.g. radar), operations of spacecraft (telecommand, telemetry, maneuvering) and payload data downlink.

Naturally, the RF spectrum that is available for satellite communications is limited. Accordingly, the bands are subdivided into certain ranges according to the spectrum needs of the various applications mentioned above. The coordinated use of the spectrum is supervised by the International Telecommunication Union (ITU). This organization established several regulations, rules and procedures called RR [10]. With the support of national administrations, the ITU processes requests from satellite developers to make use of RF spectrum. The registered use of spectrum is called filing. The ITU administers a database that contains all current filings, processes new filings and moderates between incumbent and potentially new users of frequencies.

It can be imagined that almost the complete spectrum that is generally feasible for satellite communication is highly used for one or multiple of the above-mentioned applications. All frequencies are fiercely contested and operators of both terrestrial and satellite systems nowadays need to employ frequency coordinators solely to protect their currently used frequencies.

All of a sudden there is a new competitor for spectrum in form of the small satellite community. For the very early systems, the administrative side and the developers/ operators were not sure how these systems shall be treated. As they were expected to only operate for a very limited duration and not to transmit big amounts of data, they were treated as experimental stations and often not filed at all. Since many CubeSats use Commercial Off-The-Shelf (COTS) systems that are developed for radio amateur bands, the satellites themselves were also treated as radio amateur satellites (which also have dedicated frequency allocations in the ITU Radio Regulations) [11].

In these early years of CubeSat development it was not clear for developers if they have to file their systems. If no authority asked for a filing certificate or any other proof of frequency coordination, developers tended to omit any regulatory steps. This naturally led to first cases of interference where more than one operator intended to use the same frequency and experienced disturbances from other systems. When CubeSat operators were asked to file their systems, they often did not know where to start. Universities typically do not employ experienced coordinators. New space-faring countries sometimes do not even have a national administration that is responsible for the regulatory process. And even experienced administrations were not sure about the right treatment of the satellites. This resulted in a high number of systems that were either not filed or only filed long time after the launch [11].

After several years, the correct filing of satellite systems and the right treatment of the new class of small satellites was acknowledged by most administrations and developers. However, at the same time it was realized that the existing frequency bands are already crowded and that it is very difficult to find slots for small satellites. Many of the early systems were treated as radio amateur satellites and filed in their spectrum. Since the educational component of the early satellites was prominent, this was accepted by the International Amateur Radio Union (IARU) and national radio amateur organizations. As long as the radio amateur rules were followed (e.g. no commercial service in radio amateur bands), IARU was willing to accommodate a great number of the satellites. However, as more and more systems introduced commercial components, IARU understandably prohibited the use of radio amateur bands.

Like mentioned above, the bands outside of the radio amateur bands are heavily used. At the current time it seems to be impossible to accommodate the upcoming number of hundreds of new satellites per year in the existing bands. At the same time, some of the new small satellites posed problems for other operators due to their unique characteristics and spectrum requirements. For this reason, there are ongoing studies in regulatory committees that aim to exclude small satellites from some bands that they currently operate in.

This introduction serves as the background and motivation for this thesis. The frequency coordination environment and the current and future spectrum use present new challenges for all satellite operators. The current procedures need to be investigated regarding their applicability for small satellites as well as regarding potential modifications that would simplify the introduction of small satellites and the accommodation of the increased number of satellites in the future. The next sub-chapter summarizes the approach that the author took to investigate the current and future use of frequencies for small satellite operations.

1.4 Thesis objectives

This thesis aims to examine both regulatory and technical aspects of spectrum use. The focus of this examination is on frequency bands that are commonly used by small satellites and on those bands that might be applicable for future use. The following content can be subdivided into three parts. In the first part, the needed background on small satellites as well as the regulatory environment for small satellites is given. In the second part, the results of a theoretical assessment of current and future small satellite allocations are presented. Following, two approaches for a practical implementation of a system are given which allow the analysis of the problem from the technical side.

The background in chapter 2 describes the characteristics of small satellites, the applicable regulatory environment as well as the challenges that these satellites face. The characteristics are based on a research project that has been conducted at Technische Universität (TU) Berlin and led by the author (Requirements of Pico- and Nanosatellites (REPIN)). One part of this project was the establishment of an extensive database that contains all satellites launched until 2016 as well as various parameters of each system. The second part of the research project was the investigation of the regulatory environment as well as the applicability of current regulations for small satellites. The third part of the project treated the support of national administrations in ITU study groups in order to identify challenges of small satellite developers in the frequency coordination process. In this sense, the background chapter provides the background for the investigations in chapter 3 and chapter 4, but also the results of a major part of the author's research.

Chapter 3 deals with the theoretical assessment of current and future spectrum use by small satellites. The main questions that shall be answered are:

– How much spectrum do small satellites need for their operations?

– Are the existing frequency allocations sufficient?

– Are their potential new allocations that could accommodate the growing number of small satellites?

First, an introduction into frequency coordination, i.e. the shared use of frequencies, has to be given. Following this, the spectrum that small satellites require for their use needs to be assessed. This requirement study was conducted by the author as part of another research project at TU Berlin (SALSA). The compatibility studies in chapter 3 are to a large extent conducted by other researchers that are part of an ITU study group that the author is involved in. The studies which were not the author's original work are essential for the remainder of chapter 3 and are therefore summarized and referenced accordingly. Based on the author's research as well as the results of other study groups, chapter 3 ends with an analysis of the regulatory future of small satellites.

The theoretical examinations in chapter 3 depend on the validity of historic data, assumptions and projections into the future. While theoretical studies can indicate the general applicability of bands for small satellite use, only a practical assessment can state whether the assumptions are valid. A common tool for the analysis of radio frequency use is spectrum analysis. For this task, terrestrial spectrum analyzer systems are widely used and comparatively easy to set up. However, terrestrial spectrum measurements cannot reflect the environment and interference cases in space. Consequently, an on-orbit spectrum analyzer is needed. Chapter 4 will present two approaches for an on-orbit spectrum analyzer that have been followed at TU Berlin: a spectrum analyzer satellite payload and a spectrum analyzer experiment aboard the ISS. Both systems are based on the same equipment but optimized for their specific experiment environment. The mission concept as well as further use cases for the payloads will be presented. At the time of completion of this thesis, both payloads have been implemented. The ISS payload is already launched and first flight results are available, while the satellite payload is planned to be launched in 2020.

In summary, the objectives of this thesis and the studies that were part of it are the following:

- Study and report of the characteristics and regulatory status of small satellites
- Theoretical investigation of current and potential new bands for small satellite operations
- Mission ideas and design of on-orbit spectrum analysis payloads that support the theoretical studies.

2 Background

The first part of the background section will introduce the main characteristics of small satellites, based on the TU Berlin Small Satellite Database [12] and other publications as reference below. The second part presents the required background for the frequency coordination assessment in chapter 3.

2.1 Characterization of small satellites

Detailed background on the characteristics of small satellites, especially CubeSats, can be found in a vast number of publications [6, 7, 8, 9, 12, 13, 14, 15, 16, 17]. This section summarizes the most relevant parameters from a frequency coordination perspective.

2.1.1 Classification

Satellites are traditionally classified by their mass and dimensions (table 2.1). In early years of satellite development until about 10 years ago, a small satellite was defined as a satellite with a mass of less than 500 kg. Nowadays the definition of a small satellite shifts down due to the massive increase of CubeSat deployments. The smallest casually used satellite class is the picosatellite (0.1–10 kg). There are also smaller sizes, but these are not considered to play a significant role in satellite development. Picosatellites were responsible for the first increase in satellite deployments, while today most satellites are nano- or microsatellites (approx. 5–100 kg).

2.1.2 Deployment

As stated above, in 2017 and the following years several hundred satellites will be launched per year. Most small satellites are launched piggyback by one of the main launching states: USA (SpaceX, Orbital, ...), Russia (Soyuz, ...), India (PSLV). Other launch providers (Japan, ESA, China) are also offering increased capacity for small satellite launches. The target orbit depends on the main payload of the

Satellite Class	Mass [kg]	Edge length [cm]
Picosatellite	0.1–1	5–10
Nanosatellite	1–10	10–50
Microsatellite	10–100	50–100
Minisatellite	100–1000	100–200
Traditional satellites	> 1000	> 200

Table 2.1: Satellite classes

launchers. Piggyback launches are low-weight and therefore only pay a marginal part of the launch costs, while the main amount is paid by the primary payload. Therefore both orbit and launch date are defined by the prime contractor. Almost all small satellites are launched into LEO [18]. As many traditional satellites prefer Sun-synchronous orbits, most small satellites are found in these orbits, too. Additionally, more and more satellites are deployed from the ISS. These satellites are transported to the ISS in cargo transfer vehicles (SpaceX Dragon, Orbital Cygnus, Soyuz Progress, HTV) and later deployed into defined orbits. There are some Russian launchers that deploye into orbits with an inclination of about 62 ° and some satellite launches into orbits with an inclinations of less than 20 ° for countries that are located close to the equator.

ISS deployed satellites obviously have orbits around 400 km in which they remain for only six months to two years, depending on solar activity. Due to atmospheric drag, they burn in the atmosphere after this time span. Other small satellites are usually deployed in orbits between 500 km and 650 km, where they remain for their mission lifetime and deorbit not later than 25 years after the end of mission lifetime (requirement by various authorities, e.g. European Code of Conduct [19] and Space Debris Mitigation Guidelines [20]).

2.1.3 Mission purpose

The first small satellites, especially CubeSats, were developed and operated by universities and research institutes. The mission purpose was mainly educational. Today small satellites become increasingly commercial. The number of space-faring universities and new entrants to the space sector is still rising and these developers continue to deploy satellites for educational purposes and for technology demonstration. Furthermore, commercial developers started to deploy constellations consisting of dozens of satellites (Planet, Spire, ...). These developers intend to offer commercial services, e.g. in the fields of communication or Earth observation. By launching many satellites into various orbits, daily coverage of each point on Earth can be achieved [21].

2.1.4 Spectrum characteristics of small satellite TT&C

To understand characteristics and spectrum needs of small satellites, a study has been conducted at TU Berlin under the author's lead (REPIN, BMWi grant 50 YB 1323). From 2013 until 2016 the characteristics and spectrum requirements of small satellites were investigated. The results of this project and of the work performed by the ITU-R Working Party 7B, in which the results of the projects were used, are summarized in this chapter.

The objective of the studies that were performed during the REPIN project was the assessment of typical characteristics of small satellites with a focus on the RF parameters and spectrum characteristics. For this, an extensive database of launched small satellites was established. The baseline for the database is the database of the Union of Concerned Scientists (UCS) [22]. This database aims to collect all satellites that have ever been launched and is regularly updated. For REPIN, all satellites with a mass of more than 30 kg and all satellites that have been launched before 2003 were neglected. This was done to focus on small satellites and to highlight the characteristics of modern systems that follow the CubeSat design philosophy. The data of the UCS database was complemented by some satellites systems that were missing as well as additional information on the current orbit, the mission purpose, the RF systems and more. The data was mainly obtained by direct contact with the satellite developers, complemented by various online databases and publications [6, 7, 8, 9, 12, 13, 14, 15, 16, 17]. After the database was first maintained in form of an excel sheet for about one year, it became clear that its complexity necessitated a more sophisticated format. For this reason, a Structured Query Language (SQL) database was created by Funke et al. to add more details of the captured systems and allow improved analysis [23]. Excerpts of the database are available online [12], additional analyses and status of the database were regularly published [11, 18, 24, 25, 26, 27, 28, 29, 30]. The database was the main source for two reports that were drafted in ITU-R working party 7B to bundle the available information on the characteristics of pico- and nanosatellites [31] and on the current practice in filing these systems [32].

An overview of typical small satellite characteristics is given in table 2.2. It shall be noted that the studies were performed when small satellites were mainly used for

Parameter	Value
Necessary bandwidth	$\leq$ 15 kHz
Space station RF output power	$\leq$ 1 W
Space station antenna gain	$\leq$ 3 dBi
Space station antenna type	Monopole/ Dipole, Quasi-Omnidirectional
Space station antenna polarization	Linear
Earth station system noise temperature	VHF: 1 500 K UHF: 500 K
Earth station antenna type	Yagi-Uda
Earth station peak antenna gain	10–17 dBi; typically 12 dBi
Earth station antenna 3 dB beam width	30 ° (UHF) to 50 ° (VHF)
Earth station antenna polarization	Circular
Earth station minimum elevation angle	5 °
Earth station RF output power	$\leq$ 50 W
Earth station antenna pattern	ITU-R F.699-7 (tracking antenna)
Pointing losses	1–3 dB
C-N objective	
Downlink	12 dB
Uplink	12–20 dB

Table 2.2: Typical small satellite RF characteristics [31]

educational purposes and technology demonstration. In these times, only comparably low frequencies (below 1 GHz) were used. Nowadays commercial systems and more sophisticated CubeSats use S-band and even X-band frequencies. However, many systems still use the frequencies below 1 GHz for Tracking, Telemetry & Command (TT&C), at least as backup option. Since the bands below 1 GHz are heavily crowded, studies presented in this chapter focus on TT&C below 1 GHz.

The bands below 1 GHz are mainly used for TT&C. This includes commanding the satellite and receiving telemetry (housekeeping data), e.g. temperatures, power capacity and consumption, subsystem status and more. Most systems transmit with data rates between 1.2 kbps and 9.6 kbps. Depending on the modulation method, up to approximately 15 kHz are required for these data-rates. Additional frequency requirements due to Doppler effects (approx. ± 8 kHz) are not included.

The RF output power of the satellite transmitter is usually less than 1 W, with most systems transmitting between 0.1 W and 0.5 W. The antennas for transmission are typically either monopoles or dipoles, accordingly the transmission is quasi-omnidirectional and the antenna gain is less than 3 dBi. Most antennas are linearly polarized.

The ground station on the other side can use higher RF output powers of 50 W to 100 W, depending on the required link margin. The antennas are bigger, typically (stacked) Yagi-Uda antennas with gains between 10 dBi and 17 dBi. As the satellite antennas are linear, but not always attitude-stabilized, the ground station is circular polarized.

2.2 Frequency coordination & regulatory environment

This section shall provide an introduction into frequency coordination and the regulatory environment for small satellites with a focus on LEO systems. It will present the structure of the ITU as well as the ITU approach to review and update regulatory procedures. Although the structure of the ITU is not inherently needed to understand sharing studies, it gives an understanding on how the sharing studies were conducted and on the involved parties of the studies.

2.2.1 Work flow of the ITU-R and WRC

The shared use of the frequency spectrum (both terrestrial and satellite) is coordinated by the ITU. The Radiocommunication Sector (ITU-R) established the RR which contain all rules that are applicable for spectrum use. The application of the Radio Regulations is agreed by 193 member states [33]. Naturally, the use of spectrum changes with the advance of technology and the emerge of new applications. Higher bands become available for radiocommunication services and new allocations have to be distributed. At the same time, lower band services might not be used anymore and bands can be redistributed. For example, currently the rise of new applications in the fields of Internet of Things (IoT) and Machine-to-Machine (M2M) applications makes administrations look for new allocations for 5G bands under the pressure of commercial shareholders. These reasons necessitate the continuous revision of the Radio Regulations. Every three to four years the ITU invites administrations for the World Radiocommunication Conferences (WRC). About 3000-4000 delegates meet for about four weeks to discuss potential changes of the RR. The delegations of each country vary in size and consist of members of the administrations and delegates from industry, research institutes, military and agencies. However, each of the 193 member states has only one vote in the final decisions which are build on consensus. Since the potential changes normally require careful examination on the effects on current use, study groups meet between the WRC to develop studies and recommendations. This section explains the work flow of the ITU-R and its study groups.

While half of the time allocated for a WRC is used to discuss the results of previous agenda items, the other half is spent to discuss potential new changes and the required studies. There are always multiple issues that different administrations bring up, but as the study groups have a limited number of participants, only the most relevant topics can be chosen to be studies. About 10 to 20 issues (so-called agenda items) are agreed by the WRC to be studied for the next cycle. These agenda items are agreed by all member states. A resolution is drafted for each agenda item which provides some background on the study issue and involves member states and study groups to discuss certain issues.

The following box presents the resolution that was brought up at WRC-12 in order to study the regulatory treatment of nanosatellites and picosatellites [34]:

RESOLUTION 757 (WRC-12)

Regulatory aspects for nanosatellites and picosatellites

The World Radiocommunication Conference (Geneva, 2012),

considering

a) that nanosatellites and picosatellites, commonly described as ranging in mass from 0.1 to 10 kg and measuring less than 0.5 m in any linear dimension, have physical characteristics that differ from those of larger satellites;

b) that nanosatellites and picosatellites are satellites which typically have a short (1–2 years) development time and are low cost, often using off-the-shelf components;

c) that the operational lifetime of these satellites ranges from several weeks up to a few (< 5) years depending on their mission;

d) that nanosatellites and picosatellites are being used for a wide variety of missions and applications, including remote sensing, space weather research, upper atmosphere research, astronomy, communications, technology demonstration and education, as well as commercial applications, and therefore may operate under various radiocommunication services;

e) that these satellites are typically launched as secondary payloads;

f) that some missions performed with these satellites require the simultaneous launch and operation of several such satellites;

g) that, currently, many nanosatellites and picosatellites use spectrum allocated to the amateur satellite service and the MetSat service in the frequency range 30–3 000 MHz although their missions are potentially inconsistent with these services;

h) that nanosatellites and picosatellites may have limited orbit control capabilities and therefore have unique orbital characteristics;

i) that the standing Agenda item 7 of WRCs has up to now not led to consideration of regulatory procedures for notifying nanosatellites and picosatellites, *further considering*

a) that successful and timely development and operation of picosatellites and nanosatellites may require regulatory procedures which take account of the short development cycle, the short lifetimes and the typical missions of such satellites;

b) that the existing provisions of the Radio Regulations for coordination and notification of satellites under Articles 9 and 11 may need to be adapted to take account of the nature of these satellites,

resolves to invite WRC-18

to consider whether modifications to the regulatory procedures for notifying satellite networks are needed to facilitate the deployment and operation of nanosatellites and picosatellites, and to take the appropriate actions,

invites ITU-R

to examine the procedures for notifying space networks and consider possible modifications to enable the deployment and operation of nanosatellites and picosatellites, taking into account the short development time, short mission time and unique orbital characteristics,

instructs the Director of the Radiocommunication Bureau

to report to WRC-15 on the results of these studies,

invites administrations and Sector Members

to participate actively in the studies by submitting contributions to ITU-R.

In brief, the ITU-R became aware of the fact that pico- and nanosatellites are currently not filed correctly and that operators and administrations struggle with the right application of the procedures. Therefore, the WRC asks the study groups to study the applicability of the RR and report to WRC-15 on the results of the study results. As there are 10 to 20 agenda items which involve different groups of experts, the studies are distributed into several study groups:

- Study Group 1 (SG 1): Spectrum management
- Study Group 3 (SG 3): Radiowave propagation
- Study Group 4 (SG 4): Satellite services
- Study Group 5 (SG 5): Terrestrial services
- Study Group 6 (SG 6): Broadcasting services
- Study Group 7 (SG 7): Science services

Each of the study groups is further divided into various working groups. The pico- and nanosatellite issues were assigned to Study Group 7 and are studied in ITU-R WP7B. In general, it would have been possible to discuss this matter in other groups, e.g. Study Group 4, as well, but the assignment was based such that all study groups have approximately equal work loads. The other study groups are informed about the progress after each bi-annual meeting. For each WP7B meeting, approximately 70 delegates from various countries come to Geneva, Switzerland, for about one week to discuss intermediate results. Before these international meetings, studies are discussed on a national level (*Arbeitskreise* for the German case [35]) and on a regional level (CEPT CPG meetings for the European case [36]). All of these groups do decision-making by consensus, which results in long-standing discussions and negotiations. To support the study groups and prepare the study results for the WRC, two Conference Preparatory Meeting (CPM) are held (one shortly after each WRC, the other half a year before each WRC).

In fact, there are even more groups that are involved and studies can be influenced on various levels. Administrations try to team up to defend their interests against other administrations, while at the same time interest groups (e.g. science, military, radio astronomy, amateur radio, ...) are also allied. However, the main work is done in the study groups and result in study reports like the ones mentioned above

Abbreviation	Service
FSS	Fixed Satellite Service (Feeder Links, Data Relais, Remote stations, mainly for geostationary systems)
MSS	Mobile Satellite Service
BSS	Broadcast Satellite Service (TV, Radio)
SOS	Space Operation Service (TT&C)
SRS	Space Research Service
EOSS/EESS	Earth Observation/Exploration Satellite Service
Amateur	Amateur-Satellite Service

Table 2.3: Radiocommunication services

on pico- and nanosatellites RF characteristics [31] and current practice in filing them [32].

2.2.2 Radiocommunication services

As mentioned before, the use of the available spectrum is subdivided into various allocations for different services. Services can be terrestrial or satellite-based applications. The most important satellite services are summarized in table 2.3. A radiocommunication service is defined by the ITU Radio Regulations as a "service [...] involving the transmission, emission and/or reception of radio waves for specific telecommunication purposes" [10]. The services that are mainly used by small satellites are Space operation service (SOS), Space Research service (SRS), Earth observation satellite service (EOSS), Earth-exploration satellite Service (EESS) and Amateur-Satellite Services. Spectrum is allocated in the downlink (space-to-Earth), uplink (Earth-to-space) and inter-satellite (space-to-space) direction. Since in many cases a space-to-Earth link does not interfere with terrestrial or Earth-to-space direction links, more than one service can share the same frequency allocation. Additionally, some service operators agreed to share bands even in the same direction (e.g. Earth-to-space) to use the spectrum more efficiently. The result is the co-sharing of frequency allocations between different services. Often the allocations were established on primary, secondary and tertiary basis. A primary service has privileged rights in the bands, while a secondary or tertiary service is not allowed to harmfully interfere with the primary service(s). Additional restrictions can be added to the ITU frequency allocations as footnotes, e.g. footnote 5.282 defines the use of some bands for amateur-satellite service:

"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 in accordance with 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." [10]

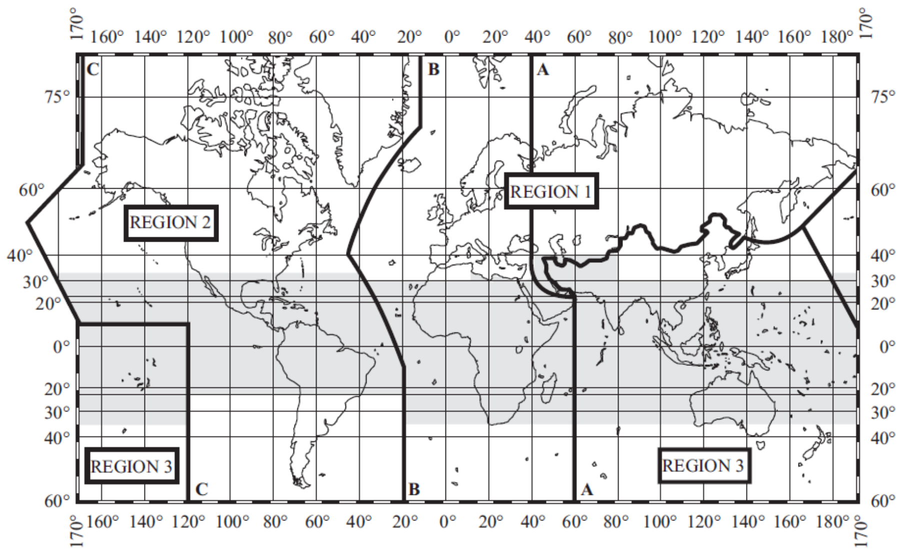

Figure 2.1: ITU-R regions [10]. The three regions have been implemented to incorporate regional variations in spectrum use.

Although it is tried to harmonize the spectrum use globally, in some cases the actual use differs between countries or even continents. Therefore the ITU established three spatial regions: Region 1 includes Europe, Russia and Africa, Region 2 includes North America, Central America and South America and Region 3 includes Asia and Oceania (figure 2.1). The ITU frequency allocation table divides all allocation into these three regions. An example is given in table 2.4. Capitalized services are primary, while the numbers (e.g. 5.268) denote the footnotes. For some allocations, footnotes add or exclude the use of certain spectrum portions in some countries, as in the example of footnote 5.282 which was quoted above.

<table>
<tr><th>Region 1</th><th>Region 2</th><th>Region 3</th></tr>
<tr><td>410–420</td><td colspan="2">FIXED
MOBILE exception aeronautical mobile
SPACE RESEARCH (space-to-space) 5.268</td></tr>
<tr><td>420–430</td><td colspan="2">FIXED
MOBILE exception aeronautical mobile
SPACE RESEARCH (space-to-space)
5.269 5.270 5.271</td></tr>
<tr><td>430–432
AMATEUR
RADIOLOCATION
5.271 5.272 5.273 5.274 5.275 5.276 5.277</td><td colspan="2">430–432
RADIOLOCATION
Amateur
5.271 5.276 5.278 5.279</td></tr>
<tr><td>432–438
AMATEUR
RADIOLOCATION
Earth exploration-satellite (active) 5.279A
5.138 5.271 5.272 5.276 5.277 5.280 5.281 5.282</td><td colspan="2">432–438
RADIOLOCATION
Amateur
Earth exploration-satellite (active) 5.279A
5.271 5.276 5.278 5.279 5.281 5.282</td></tr>
</table>

Table 2.4: Excerpt of ITU-R frequency allocation table [10]

2.2.3 Amateur-satellite service

As the amateur-satellite service is still widely (and often wrongly) used by small satellite operators, the rules and limitations of this service have to be highlighted. The amateur service is defined as *"a radiocommunication service for the purpose of 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"* ([10], Article 1.56). The amateur-*satellite* service is defined as a service that uses space stations of Earth satellites for the same purpose as defined in ITU RR Art. 1.56. The applicable rules for amateur(-satellite) systems are stated in ITU RR Article 25 and the most important points are summarized below:

- Transmissions in the amateur(-satellite) service shall be limited to applications that are in line with the amateur service purposes and remark a personal character.
- Transmissions shall not be encoded, except for the control of space stations (uplink commands can be encoded).
- Operators have to possess a valid amateur license.
- Maximum power limits and other restrictions shall be established by national administrations.
- Automatically or remote-controlled stations are only allowed under certain circumstances.
- Any commercial use is prohibited.

It is obvious that these rules do not fit the needs of commercial users. Still, due to the low complexity of amateur systems and the easy access of low cost hardware, many operators intend to use amateur bands. This trend was augmented by the fact that for early CubeSat systems, rules were not always enforced by ITU, IARU, national administrations and operators. This led to the misbelief that amateur bands are license-free bands that are available for everybody. Nowadays the rules are enforced more strictly and therefore the IARU often prohibits the use of their bands by commercial operators, even if they have licensed amateur operators in their teams.

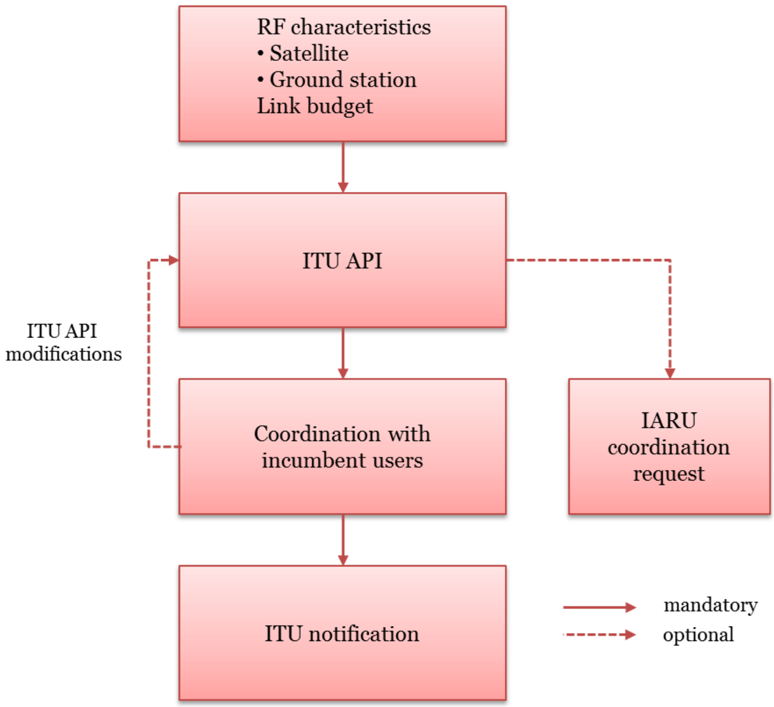

Figure 2.2: Simplified filing process for LEO satellites.

2.2.4 Filing of satellite systems

This section shall summarize the filing process for satellite systems (and their ground stations). The filing process is different for so-called planned bands (broadcasting and fixed satellite systems) and unplanned bands. The complexity of the process depends on the allocations that are planned to be used. This introduction focuses on the filing process for allocations that small satellites typically use (SOS, SRS, EOSS, EESS, amateur-satellite) for which the filing process is less complex. ITU Radio Regulations [10] and [37] provide additional information on the matter.

Each intended use of spectrum that has an impact exceeding national borders has to be filed with the ITU. It is important that the whole filing process and communication with the ITU can only be conducted through the responsible national administration. Many new operators tend to forget this fact and try to directly contact the ITU and consequently get rejected without technical examination. For Germany, the BNetzA is the responsible administration. Additional national procedures (and costs) might apply as well. The simplified procedure for non-geostationary satellites is visualized in figure 2.2. The first step is to send an initial announcement of the intended use of a slot in an allocation, which is called API. This document can be created using ITU software tools (SpaceCap) that are provided by the ITU-R Radiocommunication Bureau (BR). The API contains mandatory information on the satellite system like the operator, the orbit information (number of satellites, altitude, inclination,...), the number of links and their RF characteristics (frequency range, type of service, RF power, bandwidth, modulation technique, polarization,...) and details on the corresponding Earth stations (location, beam width,...). All mandatory and optional items can be found in the ITU RR (Appendix 4, Annex 2). The most relevant parameters for non-geostationary (NGSO) small satellites are summarized in table 2.5.

Parameter	Description
General	
Administration	Administration that is responsible for the filing (Example: Germany)
Orbit information	Number of satellites and orbital planes, altitude, inclination, orbit period, ...
Satellite	(for each beam)
General	Class of station and service (research, amateur, ...), duty cycle
RF parameters	Antenna gain, frequency, radiation pattern, bandwidth, modulation technique, polarization, peak envelope power, power density, required C-N, ...
Ground station	(for each beam)
General	longitude, latitude, country, class of station
RF parameters	antenna gain, beam width, radiation pattern, system noise temperature

Table 2.5: Most important mandatory items for API submission [10] (ITU-R RR Appendix 4, Annex 2)

Once the API is created and verified (e.g. using ITU BR's SpaceVal tool) the API can be sent to the ITU-R BR. The BR formally checks the API another time and publishes it in an online register (as API/A). After the API has been published in this register, incumbent users of the same frequency band have the right to comment on the intended use, e.g. if they see potential for harmful interference for their systems. In practice, most incumbent users comment on each new API, even without technical examination, in order to defend their bands. The potential new user has to provide further explanation that incumbent systems are not harmfully interfered by their new system. After all complaints have been dissolved, the ITU-R BR publishes a second version of the API (API/B). The operator can now submit the so-called notification which is an updated and precised version of the API information. While in the API it is enough to provide a frequency range in which the satellite system can operate, a precise (and final) frequency has to be filed. This two-step approach allows to coordinate spectrum use more efficiently. After the notification has been submitted to the ITU-R BR, it will be published and if there are no remaining issues with the intended use, the frequency is assigned to the national administration which can then officially allow the operator to use the frequency assignment. In some cases, there are remaining issues with the intended use which will be identified in the notification – however the notification will still be published. In practice, coordinators try to prevent this in a constructive manner, but depending on how crowded the band is and how potentially harmful the new system can be, not all issues can be resolved.

The coordination of new and incumbent users shall be done between the national administrations which tend to forward this task to the operators or their frequency managers. The ITU-R BR only serves as an agent. For spacerResearch bands, most national space administrations agreed to pre-coordinate their use in the Space Frequency Coordination Group (SFCG). For amateur-satellite bands, the IARU was established to coordinate amateur systems amongst themselves. This does not supersede the ITU process, but augments it. Once the API is published, the amateur operator has to send a coordination request to the IARU satellite advisory panel which will try to find available slots between the existing users.

2.2.5 Challenges for small satellite operators

Although this section is included in the *background* chapter of this thesis, it is the first result of the research within the scope of this work. In order to assess the practical applicability of the existing regulatory procedures for the new class of (very) small satellites, the challenges of small satellite operators have been assessed and shall be summarized below, categorized into aspects of (lacking) knowledge, timeline and correct application of the procedures.

Lack of knowledge

The first and most impacting challenge for small satellite developers is the lack of knowledge and experience in frequency coordination. Traditional satellite operators have vast experience in the filing process of satellite systems. Bigger companies and space agencies have dedicated frequency managers who are aware of regulatory timelines and know the mandatory steps from API to notification. These experts coordinate their systems with other users continuously and know the rules for avoiding harmful interference. Small satellite developer teams usually consist of only few people who are assigned to various tasks in the field of project management and systems engineering at the same time. For this reason, the need for frequency coordination is often overseen while working on other duties. Additionally, the applicable rules are not known to the developing teams. Only few universities teach the mandatory steps for frequency coordination as part of their curriculum. Learning all rules takes a long time, the ITU even provides seminars for this and it is likely that small satellite developers do not take part in these seminars. When developers asked the ITU or national administrations for help, it was reported that they often were pointed to the ITU Radio Regulations which are so extensive and overwhelming that the applicable procedures are hard to be identified. Another important aspect is the lack of knowledge or experience of the national administrations which shall file the satellites with the ITU-R. For some countries, small satellites were the first satellites to be launched into space and therefore either no national responsible administration existed or the national administration never filed a satellite system before. This resulted in complete filing omissions or at least in delays during the filing process.

The ITU-R study groups identified these serious deficits and therefore drafted an ITU-R resolution [38] that was to large extents co-authored by this thesis' author and is therefore presented below. The resolution was distributed to administrations via the ITU-R BR to raise awareness of the mandatory regulatory procedures.

RESOLUTION ITU-R 68

Improving the dissemination of knowledge concerning the applicable regulatory procedures for small satellites, including nanosatellites and picosatellites (2015)

The ITU Radiocommunication Assembly,

considering

a) that some developers and manufacturers of small satellites (usually having a mass of less than 100 kg), including those also known as nanosatellites (typically 1 to 10 kg in mass) and picosatellites (typically 0.1 to 1 kg in mass), may not be aware of the applicable ITU regulatory procedures;

b) that some administrations may benefit from additional information regarding application of the ITU regulatory procedures for spectrum and orbit use;

c) that lack of knowledge of the ITU procedures may lead to notification delays and sometimes launch of these types of satellite without following the applicable regulatory procedures, which may create a risk of interference to other satellite networks,

further considering

a) that, in accordance with Article 8 of the Radio Regulations: "The international rights and obligations of administrations in respect of their own and other administrations' frequency assignments shall be derived from recording of those assignments in the Master International Frequency Register (MIFR)";

b) that, for any satellite system, the recording of assignments requires fulfillment of provisions under Articles 9 and 11 of the Radio Regulations, as appropriate;

c) that it is important to ensure that any satellite radio-frequency operation (including those of nanosatellites and picosatellites) avoids harmful interference to other systems and services;

d) that the relevant ITU satellite registration (e.g. filings, recording in the MIFR) should be performed in a timely manner;

e) that it is important that the administrations involved, as well as developers, be aware of the applicable ITU processes with regard to the practices mentioned in further considering d);

f) that any satellite, including small satellites such as nanosatellites and picosatellites, should use radio frequencies in accordance with the Radio Regulations and ITU-R Recommendations, where applicable;

g) that many small satellites have no propulsion system and are therefore unable to maintain a constant orbital altitude,

recognizing

a) that the number of small satellites (in particular, satellites whose mass is typically less than 100 kg) already launched and to be launched is growing;

b) that these types of satellites can provide an affordable means to access orbital resources (spectrum and orbit) for new entrants in space;

c) that, even though satellite mass and size are not relevant from a frequency management perspective, the small mass and small dimensions of these satellites have been some of the major contributors to their success amongst new space-faring nations,

recognizing further the application of RR No. 22.1 and 25.11 for space stations,

noting the "Guidance on Space Object Registration and Frequency Management for Small and Very Small Satellites" developed by the UN Office for Outer Space Affairs and ITU,

resolves to develop material, such as Recommendations, Reports or a Handbook on small satellites (in particular, satellites whose mass is less than 100 kg), containing detailed information that would help to improve knowledge of the applicable procedures for submitting filings of satellite networks to ITU, *invites administrations*

1. to inform their national entities involved in the development, manufacturing, operation and launch of small satellites, in particular of those satellites whose mass is less than 100 kg (such as nanosatellites and picosatellites), about the applicable ITU and national regulatory provisions for the coordination, notification and use of orbital resources (i.e. orbits and frequencies);
2. to encourage their national entities aiming to launch and deploy in outer space the satellites mentioned above to initiate the relevant ITU registration procedures as soon as possible before the launch of the satellite, requests the Secretary-General to bring this resolution to the attention of the United Nations Committee On Peaceful Use of Outer Space.

Regulatory timeline of the filing process vs. development timeline

Figure 2.3 visualizes the duration of the ITU-R filing process. After the API has been submitted to the ITU-R BR, the Bureau claims to need not more than three months to publish the API/A. In reality, this highly depends on the number of filings that the Bureau needs to check and publish. As currently more and more systems are submitted, often in form of mega constellations with hundreds of satellites, the API/A will not be published before the stated three months and in some cases even later. After the API/A has been published, incumbent users of the band(s) in which the new system shall operate have four months to indicate that potential harmful interferences are suspected. The Bureau publishes the API/B after four months and forwards the concerns to the submitting administrations with the request to answer and resolve these difficulties. Even if the API is submitted quickly and all difficulties are resolved in a fast manner, the notification cannot be submitted earlier than six months after the submission of the API. After an additional time of max. two months, the Bureau publishes the notification as received. In the following, the Bureau examines the filing, compares it to raised concerns and than enters the filing into the ITU MIFR, either stating that the filing is valid with no difficulties or in a special section that some difficulties could not be resolved. In the later case, additional rules apply which would fill another book of procedures, however in most cases all administrations do their best to prevent this case. In conclusion, in the best case the filing can be finished in approximately eight months, if there are no delays in the various processes and examinations.

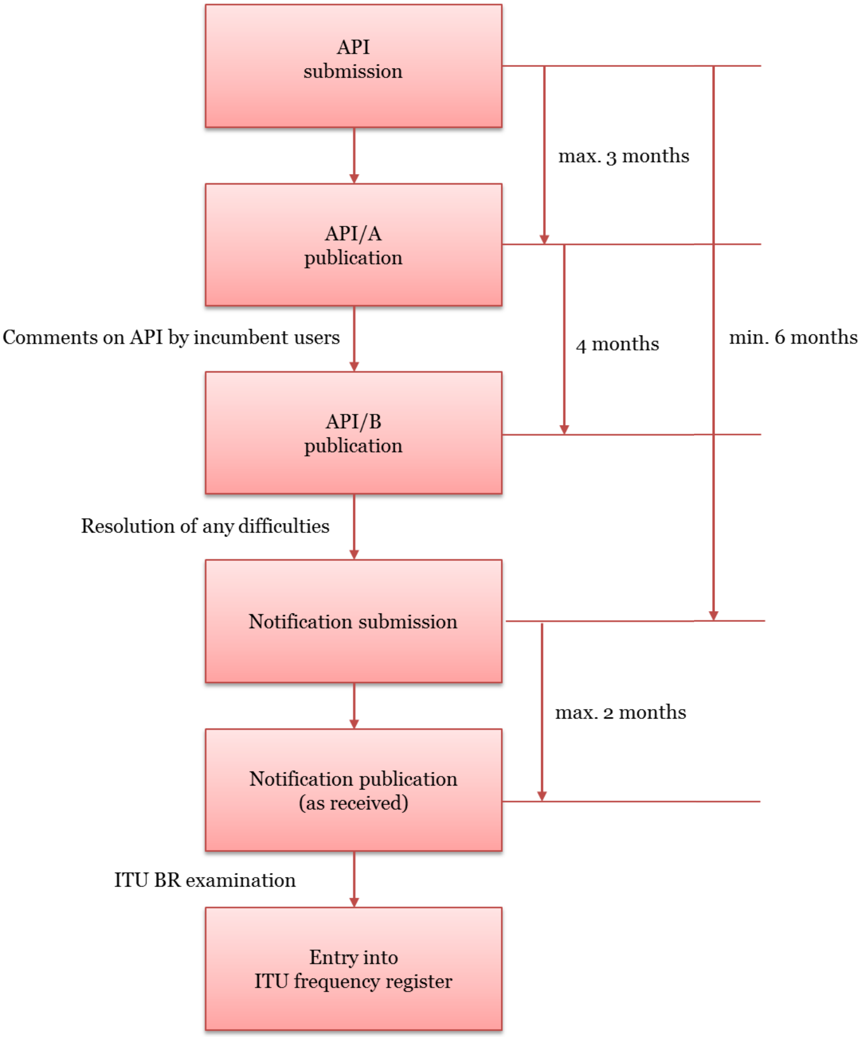

Figure 2.3: Regulatory timeline for ITU filing process

In practice, the above-mentioned eight months are far from reality. It has to be noted that before the API is submitted to the ITU-R BR, it has to be sent to the national administration by the satellite developer and the national administration has to check the filing. The correspondence between developer and administration often takes at least several weeks. As mentioned above, the Bureau might need more than three months to publish the API/A. The concerns by incumbent users need to be forwarded to the developers by the national administration, which in turn prepare responses for the concerns and forward them to their administrations, which again forward them to the incumbent users (through the incumbent user's administration). Obviously, this process further delays the whole process. The same delays can be expected in the submission of the notification and potential further inquiries during the examination of the filing by the ITU-R BR. To summarize, the complete filing process highly depends on the response time of satellite developers, national administrations, Bureau and incumbent users. There is no verified case in which the filing process was finished within 8 months. For this reason, it needs to be examined how satellite developers can accelerate the process.

Knowing that the filing process usually needs at least one year, it has to be reviewed at which phase of satellite design it has to be initiated. Although it is claimed that small satellite projects (especially CubeSats) can be developed in not more than six months, the complete process from project kick-off to the satellite launch still takes much longer, usually at least two to three years. During early project phases, the (unexperienced) small satellite developers commonly deal with non-regulatory tasks like project management, drafting requirements, concept development, preliminary design. As frequency coordination and filing processes are still considered to be a negligible or at least deferrable matter, its initiation is shifted to later project phases. This is amplified by the fact that no external authority puts pressure on the developers to initiate the process. The first time that external authorities ask for frequency and filing matters is during the negotiations for a launch with the launch provider. Most developers start these negotiations comparatively late, since project delays cannot be predicted and since no developer wants to fix a launch date before it is sure that the system is ready before launch. It is often the case that developers only initiate the filing process when launch providers ask for it, thus facing the fact that there is not much time left to finish the filing before launch.

Before any frequency can be used, the filing process has to be completed in form of an official frequency assignment by the ITU-R BR. This is done by filing the system in the MIFR, as explained above. However, most launch providers only ask for the ITU-R API. They are either not familiar with the filing process themselves or they know that the developers normally have not completed the process and try to avoid empty slots on the rockets and unsatisfied customers. This leads to the common misunderstanding that developers think that the API is enough for the use of frequencies. As a result, many small satellite systems do not have a valid frequency assignment before launch and if national administrations do not put pressure on the developers, the filing is not completed. The ITU-R databases (Space Network System [39]) show various examples of satellite systems that are in space and operating with the notification still pending.

A major impact of late initiation of the filing process is the fact that incumbent users or regulatory constraints might require change of RF parameters of the intended frequency use. If the filing process indicates that the new system needs to move to another frequency, in the worst case the hardware needs to be modified. Accordingly, an early initiation is required to allow changes of the satellite hardware.

Correct application of procedures

This chapter shall summarize the most important steps to apply the regulatory procedures correctly. It aims to merge regulatory timeline and project development timeline and gives guidance on the avoidance on common misunderstandings between developers and regulatory authorities. If the steps that are presented in this chapter are followed, the probability of a timely filing of the satellite system is significantly raised.

Choice of service

One of the early tasks is to define the service under which the satellite system shall operate. In each band (VHF, UHF, S band, X band, ...) there are spectrum portions that can be used for various services, such as space operation service, space research service, Earth exploration-satellite service, amateur-satellite service etc. It is important to note that the amateur-satellite service has been misused in the past without consequences for the operators, however the IARU currently carefully examines every new applicant on the conformance with amateur rules. Commercial operators should keep in mind that only few commercial systems were approved for the use of amateur bands, only in the case that the operators had an amateur background and the use of the bands was for amateur purposes (digipeater, APRS, ...). Developers who are uncertain on their system's applicability might want to informally ask the IARU satellite advisory panel for feedback on the intended use. Space research is defined as a "radiocommunication service in which spacecraft or other objects in space are used for scientific or technological research purposes" [10]. As this definition leaves space for interpretation, it can in general be used for many applications. The Earth exploration-satellite service is a service "between Earth stations and one or more space stations, [...] in which information relating to the characteristics of the Earth and its natural phenomena, including data relating to the state of the environment, is obtained from active sensors or passive sensors on Earth satellites [...]" [10]. These sensors are not necessarily cameras, but can also be sensors for observations on the atmosphere, climate etc. Many current small satellite missions should be compliant with this service. The space operation service is a service "concerned exclusively with the operation of spacecraft, in particular space tracking, space telemetry and space telecommand" [10]. Accordingly, it can be used for TT&C purposes, e.g. when TT&C is conducted in VHF/ UHF, while payload data is downlinked in higher bands.

The early choice of the correct service is important as their allocations are not always adjacent to each other. For example, if a commercial operator planned to use amateur-satellite services in the UHF allocation (435–438 MHz) and is rejected by IARU, the next applicable services (space research, Earth exploration, space operation) have UHF allocations around 400 MHz which might result in modification of transceivers and antennas. It should be noted that administrations can also allow the use of frequency on an experimental basis:

ITU RR Article 4.4*: "Administrations of the Member States shall not assign to a station any frequency in derogation of either the Table of Frequency Allocations in this Chapter or the other provisions of these Regulations, except on the express condition that such a station, when using such a frequency assignment, shall not cause harmful interference to, and shall not claim protection from harmful interference caused by, a station operating in accordance with the provisions of the Constitution, the Convention and these Regulations."* [10]

However, the application of this article is tried to be avoided as it highly increases the potential for interference and results in additional workload for administrations and ITU. Even though some countries allow the filing of experimental stations, operators should not expect that it is possible in their country. Additionally, experimental systems cannot claim protection from other users which could result in loss of data and contact times. The last common misinterpretation that should be resolved under this matter is the belief that industrial, scientific and medical (ISM) bands can be used for satellite systems. ISM is defined for local use only, satellite systems are not included.

Initiation of filing process

It should be borne in mind that the API, which is the first step of the filing, only asks for preliminary data and for some parameters even ranges (e.g. frequency range) are requested. Subsequently, the API can be submitted at a comparatively early phase of the project. As soon as the intended frequency bands and services are known, the filing process can be initiated. It is recommended by the author to start the process not later than after Phase B (as defined by the ECSS [40],[41]). This should leave enough time for the regulatory authorities and incumbent users.

Orbit information

The study of the regulatory procedures and their applicability to small satellite systems identified that the orbit information is a challenge for the timely filing of small satellites. Small satellites are launched piggyback and therefore cannot choose the final orbit. Launch providers offer slots on rockets as they become available and the final parameters like orbit altitude and inclination can only by fixed when the launch contract is signed (or even later). The late knowledge of orbit parameters and the ways that it should be dealt with was therefore discussed in ITU-R study groups. After consultation of developers and authorities it became obvious that the uncertainty of orbit parameters is mainly influencing the orbit altitude. However, the difference between launchers is usually only few tens of kilometers, e.g. 500 km for one launcher and 550 km for another launcher. Still, since small satellites naturally decay during mission lifetime, it is mandatory to submit a range for the orbit altitude. In case of uncertainty of the final orbit parameters, the ITU-R BR recommends to indicate the worst-case (highest) orbit altitude. Additionally, the minimum orbit altitude should be indicated in an extra field of the API. If their are more significant differences, for example if an sun-synchronous 500 km orbit or an ISS deployment are the launch options, it is valid to register to orbital planes for the filing and simply only use one of them with the system. This might result in higher coordination efforts with incumbent users, but at least the filing process can be initiated early enough.

RF parameters

Obviously, some RF parameters have to be defined before the filing. The modulation technique, antenna gain, output power and other parameters have to be indicated. In case of uncertainties it is recommended to just use worst-case assumptions. The ITU does not verify if all values of the real system are as indicated in the filing, as long as the real system does not exceed power levels that might interfere with other systems. If it is not known if the antenna has 0 dBi or 2.15 dBi, the worst-case for interference analysis (2.15 dBi) should be indicated. The frequency to be used should be kept as vague as possible to allow coordination for incumbent users. For example, if the transceiver and antenna can operate in the range 435 MHz to 438 MHz, this range should be indicated instead of a desired frequency, e.g. 437 MHz. In that way, the filing allows coordination. The precise frequency will later be updated in the notification form.

2.3 Relevance of background

This background section gave an overview about the RF characteristics of small satellites and introduced the ITU regulatory environment. The investigation of the mandatory items for filing has shown that all values can be indicated at an early project phase. The only parameter that was identified as problematic was the orbit altitude and the best practice for this matter was discussed with the ITU-R. Using the recommendations mentioned above, a timely filing of small satellite systems is possible. This is also the result of the WP7B studies and was confirmed at WRC-15. Subsequently, it was decided that pico- and nanosatellites do not need modifications in the regulatory procedures. However, a new challenge arose during the study cycle 2012–2015. If all small satellite developers file their systems correctly, taking into account the vast number of new satellites being launched, the RF frequency allocations become more and more crowded. Although small satellites can be treated in the same way as traditional satellites and the regulatory procedures do not need to be changed for them, it is suspected that the hundreds of new satellites will put pressure on the available frequency allocations. Therefore, the suitability of existing allocations to accommodate future systems has to be examined, which will be done in the next chapter.

3 Assessment of potential solutions for regulatory challenges

This chapter will assess potential solutions for the regulatory challenges that came up with the emerge of small satellites. As explained in chapter 2, small satellites do not differ from traditional satellites from a frequency coordination perspective and have to be treated accordingly. The development time of small satellites is much smaller than for traditional satellites, yet it is long enough to allow timely filing. The characteristics that make small satellites unique, e.g. mass and dimensions, are not relevant from a frequency coordination perspective. Still, small satellites have a major impact on the regulatory environment as hundreds of new satellites are launched each year and all of these systems need spectrum for their operations.

Section 3.1 will provide an overview of the baseline of this theoretical assessment. It describes how the studies were initiated and explains the constraints and limitations of the study. Section 3.2 gives the technical background for studies on sharing and compatibility, while section 3.3 summarizes the spectrum needs of small satellites. Section 3.4 and 3.5 explain the suitability of existing and potential new RF allocations for small satellites. The theoretical assessment is concluded with a summary and recommendations for future studies and potential changes 3.6.

3.1 Baseline

Table 3.1 summarizes the frequency allocations below 1 GHz that are currently used by small satellites. Primary allocations are printed in bold font. Additional regional allocations (defined by footnotes) are not included to focus on the global environment. Allocations with less than 50 kHz of cumulative bandwidth are also not included as these are considered to be too small to be relevant for future use by small satellites.

Band [MHz]	Service	Constraints
Uplink		
144.00–146.00	**Amateur-satellite**	
148.00–149.90	SOS	RR No. 9.21 applies
401.00–403.00	**EESS**	
435.00–438.00	Amateur-satellite	
449.75–450.25	SOS, SRS	RR No. 9.21 applies
Downlink		
137.00–138.00	**SOS**, **SRS**	
144.00–146.00	**Amateur-satellite**	
267.00–272.00	SOS	NATO harmonized band
272.00–273.00	**SOS**	NATO harmonized band
400.15–401.00	**SRS**, SOS	
401.00–402.00	**SOS**	
435.00–438.00	Amateur-satellite	
460.00–470.00	SRS	

Table 3.1: Current use of frequency allocations below 1 GHz. Primary allocations are highlighted in bold font.

A quick glance at the frequency allocations reveals that the amount of spectrum is relatively small. It is further limited by the fact that amateur-satellite allocations are not usable for many (small) satellite systems. Additionally some of the allocations are constrained (RR No. 9.21, NATO harmonized bands). The reason of these constraints will be explained in subsequent chapters, however they effect that these bands are not usable for small satellites. In conclusion, only the following allocation are usable:

- uplink direction: 401–403 MHz
- downlink direction: 137–138 MHz, 400.15–402 MHz and 460–470 MHz

During WRC-15 the question was raised if these bands are enough to accommodate the rising number of small satellites and their need for TT&C. WRC-15 decided that it must be studied if the existing frequency allocations are sufficient and Resolution 659 (WRC-15) [42] was issued. The resolution is referenced below and shall be explained in the following.

RESOLUTION 659 (WRC-15)

Studies to accommodate requirements in the space operation service for non-geostationary satellites with short duration missions

The World Radiocommunication Conference (Geneva, 2015),

considering

a) that the term "short duration mission" used in this Resolution refers to a mission having a limited period of validity of not more than typically three years;

b) that examples of such satellites are given in Report ITU-R SA.2312, which provides technical characteristics;

c) that Report ITU-R SA.2348 provides an overview of the current practice and procedures for notifying space networks currently applicable to these satellites;

d) that, since the number of these satellites is growing, the demand for suitable allocations to the space operation service may increase;

e) that it is important to ensure that any satellite radio-frequency operation avoids harmful interference to other systems and services;

f) that the frequency bands below 1 GHz are used for a wide variety of terrestrial and space applications, that some of these frequency bands are heavily used and new allocations to the space operation service in these frequency bands should not put undue constraints on incumbent services;

g) that some non-amateur satellites have used frequencies for telemetry, tracking and command in the frequency bands 144–146 MHz and 435–438 MHz which are allocated to the amateur-satellite service, and that such use is not in accordance with Nos. 1.56 and 1.57;

h) that, according to No. 1.23, telemetry, tracking and command functions for satellites will normally be provided within the service in which the space station is operating;

i) that these satellites are constrained in terms of low on-board power and low antenna gain as described in Report ITU-R SA.2312;

j) that the bandwidth currently used by these satellites for telemetry, tracking and command in frequency bands below 1 GHz, as described in Report ITU-R SA.2312, is generally 0.1 MHz or less,

further considering

a) that these satellites may provide an affordable means to access orbital resources (spectrum and orbit) for new entrants in space;

b) that the mass and dimensions of these satellites have been some of the major contributing factors to their success among new space-faring nations;

c) that the reliable control and tracking of satellites is important for the management of space debris,

recognizing

a) that the existing allocations to the space operation service below 1 GHz, where No. 9.21 applies, are not suitable for the satellites referred to in considering a) and b);

b) that there are other frequency bands already allocated to the space operation service below 1 GHz where No. 9.21 does not apply;

c) the provisions contained in No. 5.266 and No. 5.267 and Resolution 205 (Rev.WRC-15),

resolves to invite the 2019 World Radiocommunication Conference

to consider the results of ITU-R studies and take necessary action, as appropriate, provided that the results of the studies referred to in invites ITU-R below are complete and agreed by ITU-R study groups,

invites ITU-R

1. to study the spectrum requirements for telemetry, tracking and command in the space operation service for the growing number of non-GSO satellites with short duration missions, taking into account No. 1.23;

2. to assess the suitability of existing allocations to the space operation service in the frequency range below 1 GHz, taking into account recognizing a) and current use;
3. if studies of the current allocations to the space operations service indicate that requirements cannot be met under invites ITU-R 1 and 2, to conduct sharing and compatibility studies, and study mitigation techniques to protect the incumbent services, both in-band as well as in adjacent bands, in order to consider possible new allocations or an upgrade of the existing allocations to the space operation service within the frequency ranges 150.05–174 MHz and 400.15–420 MHz,

invites Member States and ITU-R Sector Members, Associates and Academia

to participate in studies by submitting contributions to ITU-R.

The first noteworthy element of the resolution is that it refers to "short duration missions" rather than small satellites. The reason for this is that small satellites – as described in previous chapters – are not comprehensible from a frequency coordination perspective. In the absence of an identifying technical parameter (like mass, dimensions, or others) it was decided that these systems can be described by their limited mission duration of typically not more than three years. For those reasons, ITU studies refer to short duration missions with a limited period of validity of not more than three years. The *considering* section of the resolution gives further background information on the characteristics of these systems, refers to the reports that have been written in the previous study cycle and explains the circumstance that many short duration missions use bands below 1 GHz, at least for their TT&C. The *recognizing* section provides additional constraints to the use of bands below 1 GHz, which will also be explained below. The most important elements of the resolution are contained in the *invites ITU-R* section, which describes the work package for the study groups:

– Study the spectrum requirements of short duration missions for TT&C
– Assess the suitability of existing frequency allocations below 1 GHz for short duration missions and
– if these allocations are not sufficient, study the feasibility of the frequency ranges 150.05–174 MHz and 400.15–420 MHz for short duration missions, taking into account existing use.

The frequency ranges 150.05–174 MHz and 400.15–420 MHz are the result of mainly political discussions during WRC-15. In the beginning it was considered to study all bands below 1 GHz, however strong opposition was built by various incumbent users, e.g. broadcasting services or governmental users. As these are supported by relatively large lobbies, it was agreed to not look into certain frequency ranges below 1 GHz. The advantage of this is the fact that the number of sharing studies to be undertaken was reduced significantly. With ITU-R Resolution 659 the study groups received a large work assignment to be fulfilled until WRC-19. The work was allocated to ITU-R Working Group 7B. Some of the results of the group, in which the author participated, are reflected in the subsequent chapter, however some basics of sharing and compatibility studies need to be introduced in advance.

3.2 Basics of sharing and compatibility studies

The background chapter already explained that two or more services can share the same frequency band. This chapter will introduce how sharing of the same band is possible without interference. The sharing scenarios will focus on NGSO satellites and exclude sharing with Fixed-Satellite Systems (FSS) and Broadcasting-Satellite Service (BSS) systems, as they should not be interfered by NGSO satellites in any case (RR Article 22 [10]). There are different reasons why two or more services can share the same frequency band:

- different direction: One service operates in the space-to-Earth direction, the other one in the Earth-to-space direction.
- spatial separation: In a certain region, a service is not heavily used, while another service is commonly used. In another region, the opposite can be the case.
- temporal separation: one service only operates during a minor duration of the day.
- coding separation: coding techniques allow simultaneous use of the same frequency band, at least for a limited number of co-existing systems.

However, when a new service (or a new system within a service) intends to share a spectrum portion, compatibility has to be examined. In other words, it has to be investigated whether sharing is possible without harmful interference. Figure 3.1 depicts all possible interference cases:

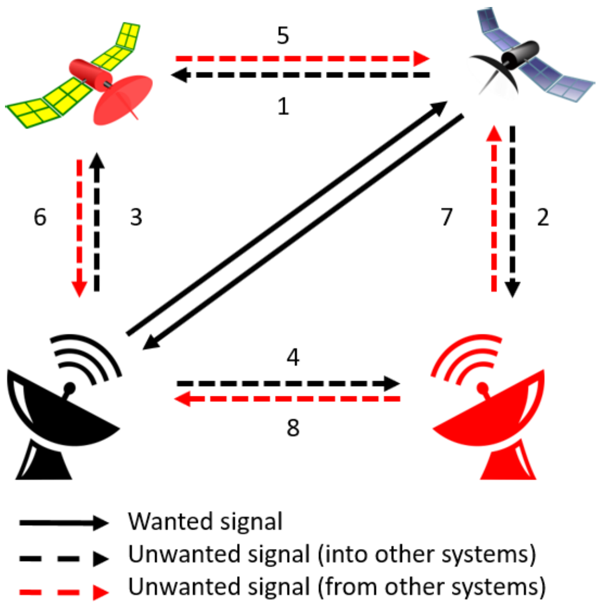

Figure 3.1: 8 potential interference scenarios

1. emissions from own satellite into other satellite
2. emissions from own satellite into other Earth station
3. emissions from own Earth station into other satellite
4. emissions from own Earth station into other Earth station
5. emissions from other satellite into own satellite
6. emissions from other satellite into own Earth station
7. emissions from other Earth station into own satellite
8. emissions from other Earth station into own Earth station

For each service, the RR define protection criteria which must be met by the other service (or by a new system within the service). These protection criteria are defined for Earth stations and space stations separately. Sharing and protection criteria shall be explained using the example of the space operation service. The characteristics including protection criteria of this service are explained in Recommendation ITU-R SA.363-5 [43]:

Earth stations: *For Earth stations carrying out space operation functions, above 1 GHz, the total interference power at the receiver input in any 1 kHz band should not exceed –184 dBW for more than 1 % of the time each day; below 1 GHz, this value may be increased by 20 dB per decreasing frequency decade.*

Space stations: *For space stations carrying out space operation functions, the ratio of signal power to total interference power in any 1 kHz band should not fall below 20 dB for a period exceeding 1 % of the time each day.*

There are different kinds of interference protection thresholds. In the SOS example, the threshold for Earth stations is defined as a power density (dBW/kHz). The threshold for the space station is given as minimum *signal-over-interference* (*C over I* or *C-I*) value. Some other recommendations for different services choose the *interference-over-noise* (*I over N* or *I/N*) or a maximum power flux density (pfd) value. All of these thresholds can be converted into each other if the characteristics of interfering and interfered systems are available. Besides interference protection thresholds, most protection criteria include a time parameter for which the threshold shall not exceeded.

In the following, a sharing study shall be explained using the example of two SOS systems. The two satellites are both located in a 300 km Sun-synchronous orbit. The "wanted" SOS ground station and the interfering ground station (IF) are both located in Germany. In practice, no operator would choose to operate co-channel with another satellite that shares the same orbit, however this example reduces the complexity of the sharing study and does not mix different interference mitigation techniques.

3.2.1 Sharing study example: Interference into space station

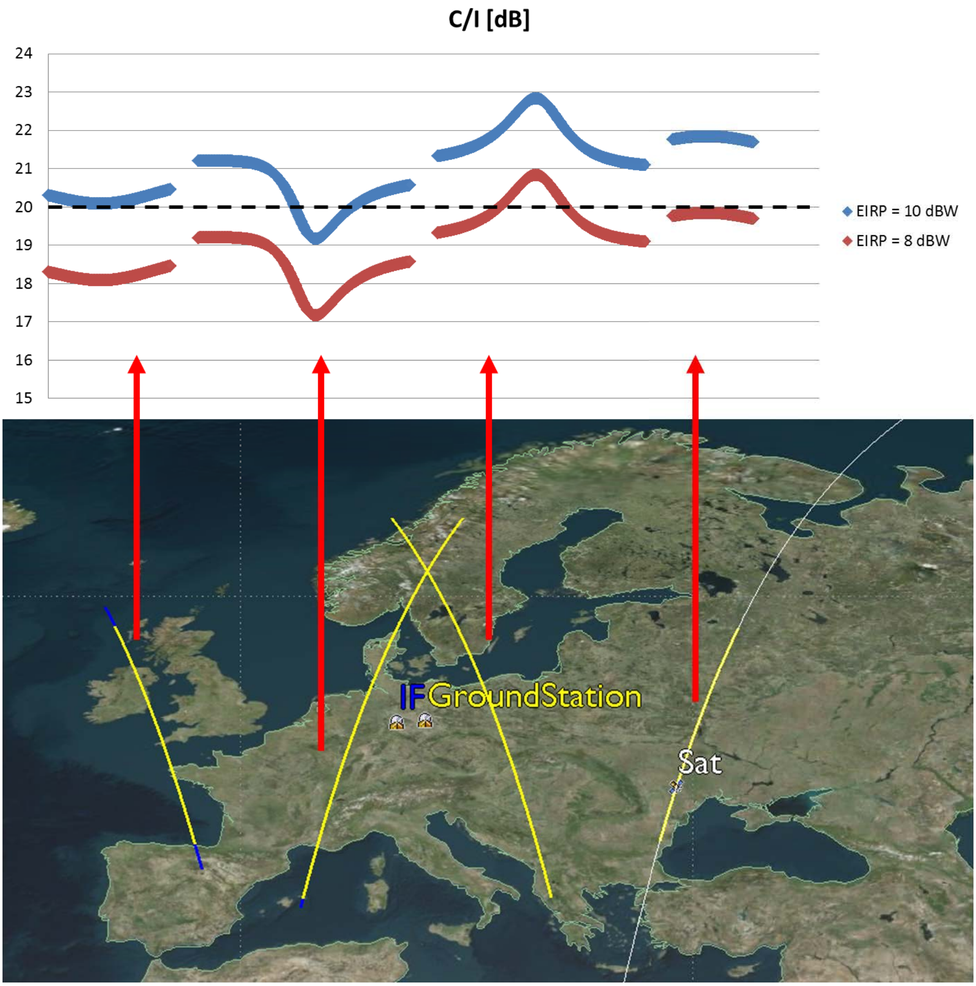

Figure 3.2: Sharing scenario between two SOS systems. As the two satellites share the exact same orbit, only one is visualized. The yellow lines represent the access times (or connection times). The C-I for two different interferer EIRP values is shown for the four passes. The protection threshold is 20 dB.

In the first case, the Earth-to-space direction of the SOS system is interfered by the IF station. The scenario is simulated for a period of 24 hours, during which the satellite passes its ground station four times (figure 3.2). The received signal power C at the space station's receiver can be calculated as

$$\begin{aligned} C &= P_{tx} + G_{tx} - L_{free\ space,tx} + G_{rx} \\ &= EIRP - L_{free\ space,tx} + G_{rx} \end{aligned} \tag{3.1}$$

The Earth station's transmit power P_{tx} is assumed to be 17 dBW, the transmit antenna gain G_{tx} is 12 dB and the frequency is chosen as 137.5 MHz. The free space loss $L_{free\ space,tx}$ is calculated based on the elevation and slant range of the SOS link. The interfering power I can consequently be calculated as

$$I = P_{if} + G_{if} - L_{free\ space,if} + G_{rx} \tag{3.2}$$

For simplicity, the interferer satellite's gain and the wanted satellite's gain are chosen to be 0 dBi (omnidirectional). This is in line with typical small satellite RF parameters. For the sharing study, C and I only need to be calculated for the time when the space station is in view of both Earth stations. An STK scenario was simulated with a time step of one second to find these access times. The resulting *C-I* for two different interferer EIRP values is depicted in figure 3.2.

The protection threshold of 20 dB is temporarily violated for both interferer EIRP values. For 8 dBW, the violated time period is calculated as 105 seconds, which corresponds to 0.12 % of the day (86400 seconds). For 10 dBW, the violated time period is calculated as 1015 seconds, which corresponds to 1.17 % of the day, which exceeds the protection limits. Consequently, in the latter case the interferer would need to reduce the output power to prevent harmful interference.

3.2.2 Sharing study example: Interference into Earth station

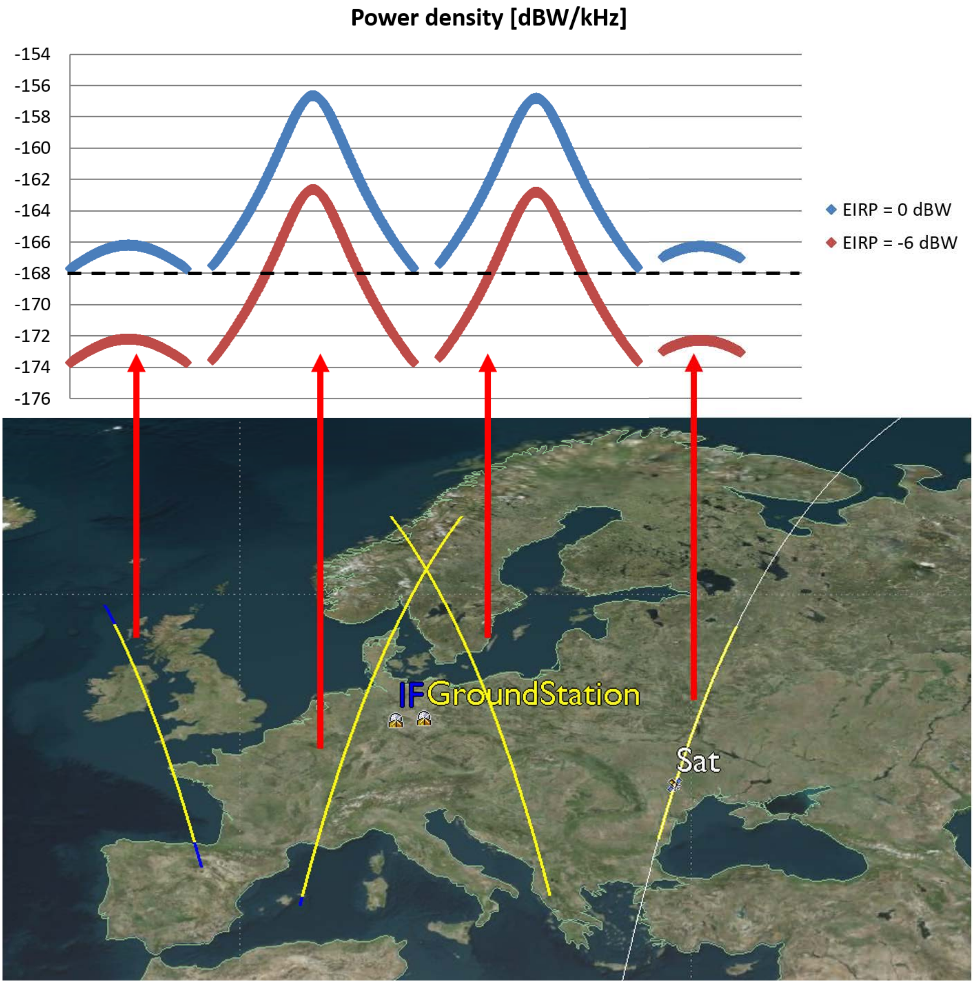

Figure 3.3: Sharing scenario between two SOS systems. Power density of transmissions from interfering satellite into ground station for two different interferer EIRP values are shown for the four passes. The protection threshold is -166.8 dBW/kHz.

For interference into the Earth station, the effect of the second satellite's transmissions into the ground station is analyzed. The protection criteria for SOS Earth stations is –184 dBW per 1 kHz above 1 GHz. For frequencies below 1 GHz, the power can be increased by 20 dB per frequency decade. If again 137.5 MHz is chosen as center frequency, the protection threshold results in

$$\begin{aligned} PSD &= -184\ dBW/kHz - 20\ LOG_{10}\left(\frac{137.5\ MHz}{1000\ MHz}\right) \\ &= -166.8\ dBW/kHz \end{aligned} \tag{3.3}$$

where PD is the power density in dBW/kHz. The received power density from the interferer satellite can be calculated as

$$PSD_I = EIRP_{IF\ Sat} - 10\ LOG_{10}(BW) - L_{free\ space} + G_{rx} \tag{3.4}$$

It is assumed that the interfering satellite uses an omnidirectional antenna. The bandwidth is 12.5 kHz and the other values remain unchanged. Figure 3.3 shows the power density at the ground station's receiver for EIRP values of 0 dBW and -6 dBW. For the first case, the threshold is violated for 1.1 % of the time (952 seconds), while for the latter case it is violated for only 0.3 % of the time (288 seconds). Consequently, a reduction of EIRP could result in potential co-channel sharing (if link budget is positive for both systems).

Obviously, the interference cases presented here are comparatively simple. In a typical case, the satellites would have different orbits, characteristics and protection criteria. The dynamic interference scenario of multiple satellites and the aggregate interference of multiple satellites would also need to be incorporated. Additionally, the interference between two or more satellites and between two or more Earth stations would need to be calculated. Sharing studies between two or more satellites are analog to sharing studies between a interfering Earth station and a space station. In sharing studies between two or more Earth stations, the common approach is to first identify the required propagation loss between the stations to meet the protection threshold. Based on this value and the terrain around the assessed Earth station, the minimum separation distance is calculated. For stations with steerable antennas and especially in case of varying surface surrounding the station, this distance varies for different azimuth angles. An ITU-R recommendation exists that provides tools to calculate the required separation distance [44]. The introduction of all cases of interference would exceed the scope of this work. For further reading, [10] and [45] are recommended.

3.3 Spectrum requirements of small satellites

An introduction into sharing and compatibility studies was given in the previous section. Given this background, the spectrum requirements of small satellites can be assessed. Based on the development of small satellite launches, it was estimated that approximately 300 pairs of satellites and Earth stations intend to use frequencies below 1 GHz for TT&C in the near future. The first task derived from ITU-R Resolution 659 was the study of spectrum requirements of small satellites (short duration missions) for TT&C. In order to perform this task, system characteristics and simulation parameters were agreed by study group WP7B. The characteristics were mainly derived from the reports of the previous study cycle [31, 32] and can be found in a new ITU report [46]. The most important parameters have already been introduced in table 2.2. The report additionally contains link budget calculations that verify that the parameters fulfill link requirements.

3.3.1 Simulation parameters

This section contains the most important parameters for the calulcation of the spectrum requirements. More details on these parameters can be found in [47] and [48].

Frequency bands

The following frequencies were chosen to calculate the spectrum requirements:

– Downlink: 137.5 MHz and 401 MHz

– Uplink: 149 MHz and 450 MHz

Theoretically, any frequency below 1 GHz could have been chosen, however it was decided to choose frequencies in which SOS allocations already exist.

Satellite orbits

The orbits of the agreed 300 satellites are based on the TU Berlin Small Satellite Database [12]. Since the database contains more than 300 satellites and some satellites share the same Earth station, for each Earth station only one corresponding satellite was chosen and some satellite systems were neglected (e.g. non-active satellites) to result in 300 satellite-Earth station pairs. In general, the real distribution based on the database could have been taken as simulation input. However, it was decided in the study group to create a more general dataset from the database information. Therefore, the distribution of satellite orbits is derived from the real scenario as depicted in table 3.2 and table 3.3. Mean anomaly, argument of periapsis and right ascension of the ascending node (RAAN) are randomly distributed between 0 and 360 degrees using uniform distribution. All orbits are assumed to be circular. The RF parameters can be derived from table 2.2 except for the fact that a transmission bandwidth of 25 kHz was chosen.

Altitude	Distribution
300–500 km	59 %
500–750 km	38 %
750–1000 km	3 %

Table 3.2: Altitude distribution of satellites for simulation (uniform distribution in each bin)

Inclination	Distribution
0-40 degree	5 %
40-60 degree	45 %
60-90 degree	5 %
90-100 degree	45 %

Table 3.3: Inclination distribution of satellites for simulation (uniform distribution in each bin)

Earth stations

The distribution of Earth stations is based on the small satellite database as well (see figure 3.4). The RF parameters can be derived from table 2.2. The radiation pattern of the Earth station antenna is derived from [49]. The equations are shown below and the resulting gain over the off-axis angle is depicted in figure 3.5.

Figure 3.4: Earth station locations as used for the simulation. The distribution is based on real locations of stations according to the TU Berlin Small Satellite Database [12].

$$G(\varphi) = G_{max} - 2.5\ 10^{-3}(\frac{D}{\lambda}\varphi)^2 \qquad \text{for } 0 \text{ deg } < \varphi < \varphi_m \tag{3.5}$$

$$G(\varphi) = G_1 \qquad \text{for } \varphi_m < \varphi < 100\ \frac{\lambda}{D} \tag{3.6}$$

$$G(\varphi) = 52 - 10\ log_{10}(\frac{D}{\lambda}) - 25\ log10(\varphi) \qquad \text{for } 100\frac{\lambda}{D} \leq \varphi < \varphi_s \tag{3.7}$$

$$G(\varphi) = -2 - 5\ log_{10}(\frac{D}{\lambda}) \qquad \text{for } \varphi_s \leq \varphi \leq 180 \text{ deg} \tag{3.8}$$

where

$$\frac{D}{\lambda} = 10^{\frac{G_{max}-7.7}{20}} \tag{3.9}$$

$$G_1 = 2 + 15\ log_{10}(\frac{D}{\lambda}) \tag{3.10}$$

$$\varphi_m = 20\frac{\lambda}{D}\sqrt{G_{max} - G_1} \tag{3.11}$$

$$\varphi_r = 15.85\ (\frac{D}{\lambda})^{-0.6} \tag{3.12}$$

$$\varphi_s = 144.5\ (\frac{D}{\lambda})^{-0.2} \tag{3.13}$$

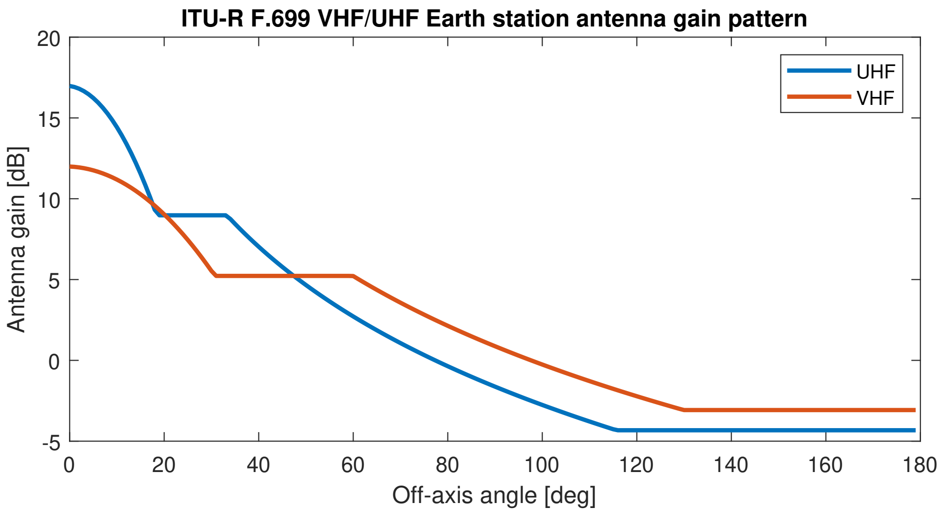

Figure 3.5: Radiation pattern of Earth station antenna based on [49]

Simulation inputs

Additional simulation inputs include the SOS protection criteria (for space station $C/I > 20$, for Earth station -166.7 dBW/kHz (VHF) and -176 dBW/kHz (UHF) based on ITU-R Recommendation SA.365), the simulation duration (seven days) and time step (ten seconds) as well as the transmission scheme. For the Earth-to-space direction, only the highest pass of each satellite over its Earth station is assessed in the study to incorporate the fact that commanding is undertaken during very short intervals of each day. For the space-to-Earth direction, two different cases are considered: One case in which only the highest pass is assessed and another case in which each pass is assessed.

3.3.2 Simulation results

The different simulation cases were distributed among study group participants. The author of this work simulated the spectrum requirements in the space-to-Earth direction for the case that all satellite passes are taken into account. To compare different simulation approaches, other study group members added their own simulations on this case, while others focused on the remaining simulation cases. It should be noted that the later simulations are not the original work of the author and more detail can be found in the relevant ITU-R reports [47].

Different approaches have been used to assess the spectrum requirements of short duration missions. The general question is how many satellites-Earth station pairs can operate co-frequency without interfering with each other. The total number of systems (300) can consequently be divided by this number and multiplied with the bandwidth (25 kHz). The result will indicate the spectrum requirements of short duration missions.

Space-to-Earth direction

The author's work includes two methods. The first method represents a worst-case scenario of randomly distributed systems, while the second method represents a best-case in which systems are distributed in a coordinated manner. These two methods have been implemented in order to provide a range from which the spectrum requirements can be derived. Since the total number of 300 systems does only provide the best-guess for the number of future system, it was considered more realistic to calculate a spectrum range based on worst-case and best-case scenarios.

Method 1

Two satellite-Earth station pairs are randomly created out of the simulation dataset. One system represents the interferer, the other system represents the interfered system. Similar to section 3.2.2, the interference into the Earth station is calculated along with the percentage of time that the protection threshold is exceeded. Since

No. of systems	2	3	4	5	6	7
Threshold exceedance (VHF)	0.42	1.17	1.53	2.29	2.36	3.64
Threshold exceedance (UHF)	0.51	0.99	1.52	1.87	2.45	3.16

Table 3.4: Results of method 1 for space-to-Earth direction. The table yields that the protection criteria threshold can be met by 3 (VHF) or 2 (UHF) systems for 1 % of the time.

the result highly depends on the random pick, 300 repetitions are made and the percentage of protection threshold exceedance time is averaged above these runs. The results are summarized in table 3.4.

Method 2

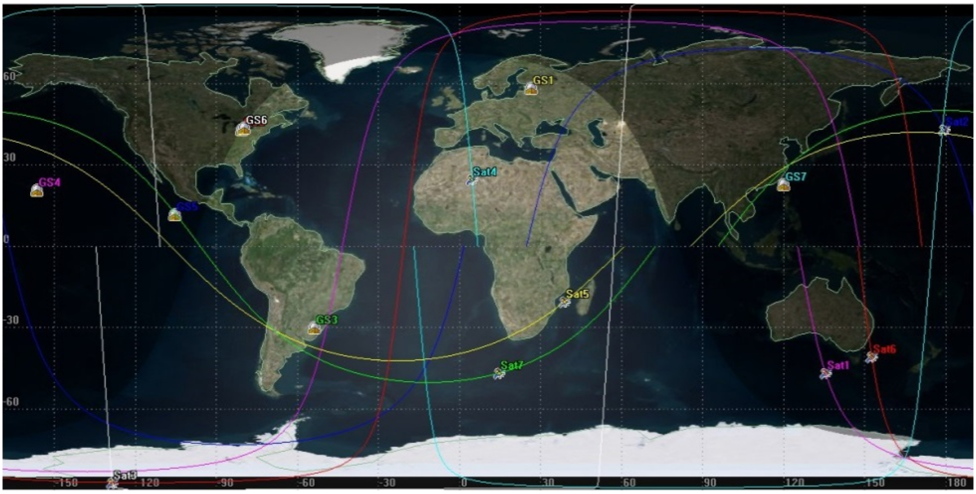

Figure 3.6: Maximum number of systems that can operate without exceedance of the protection threshold in the UHF space-to-Earth direction case [48]

The random pick is a worst-case simulation that describes a completely uncoordinated scenario. A more reasonable and more realistic approach would seek to identify a sharing scenario in which as many systems as possible operate co-frequency. For this, n satellite systems are randomly created and it is checked if the protection criteria threshold is met for 1 % of the time. This approach is repeated up to 300 times. If a case is found when n systems can operate co-frequency without exceeding the threshold, n is increased until the maximum number of co-frequency systems is found. The algorithm identified the maximum number of co-frequency systems to be five (VHF) and seven (UHF). The UHF scenario with seven co-channel systems is depicted in figure 3.6.

Comparison of worst-case and best-case study

The two studies yield that the number of co-channel systems is between two and seven systems for the UHF case and between three and five systems for the VHF case. These numbers result in spectrum requirements of 1.5–2.5 MHz in VHF and 1.07–3.75 MHz in UHF.

Results of further study

A study by another study group member took a slightly different approach [47]. A number of n systems (n ranging from 2 to 40) was randomly picked and for each of the n systems the interference was calculated. 100 simulation runs were conducted for each number n and the percentage of Earth stations at which the protection criteria was exceeded was calculated. The whole simulation set was done for the case that all passes are taken into account and for the case that only the highest pass is taken into account. Furthermore, the authors of the study claimed that since the stations were picked randomly and the whole study is rather conservative, a percentage of 30 % to 50 % of the systems could allow exceedance of the protection criteria. The study yielded that 0.625–2.5 MHz are required for the space-to-Earth direction (for both VHF and UHF).

Outcome of different studies

The best-case study (Method 2) is in line with the external study, hence 0.625–2.5 MHz was decided to be taken as the required bandwidth for SOS short duration missions in the space-to-Earth direction.

Earth-to-space direction

Simulations in the Earth-to-space direction were conducted by the same study group member as above, using the input parameters and approach which where explained above. Studies yielded that the required bandwidth for SOS short duration missions is 0.682–0.938 MHz in the Earth-to-space direction. More information can be found in the ITU-R report [47].

3.4 Suitability of existing allocations to the space operation service

0.625–2.5 MHz is needed for SOS short duration missions in the space-to-Earth direction and 0.682–0.938 MHz is needed in the Earth-to-space direction. To simplify these numbers, the study group agreed to look for 1 MHz for downlink (space-to-Earth) and 0.5–1 MHz for uplink (Earth-to-space). The next work task of Resolution 659 was to analyze the suitability of existing SOS allocations for use by short duration missions. In general, an allocation is considered to be suitable if there are no external constraints, either by regulations or by current use. All SOS allocations between 100 MHz and 1 GHz are summarized in table 3.5.

Band [MHz]	Status	Constraints
Uplink		
148.00–149.90	Primary	RR No. 9.21 applies
449.75–450.25	Primary	RR No. 9.21 applies
Downlink		
137.00–138.00	Primary	
267.00–272.00	Secondary	NATO harmonized band
272.00–273.00	Primary	NATO harmonized band
400.15–401.00	Secondary	
401.00–402.00	Primary	

Table 3.5: SOS allocations between 100 MHz and 1 GHz

In the uplink direction there are only two SOS allocations below 1 GHz. Although they are comparatively rarely used and the amount of spectrum would be sufficient to accommodate short duration missions, these band have a constraint that currently makes them unfeasible in form of RR No. 9.21. This paragraph of the Radio Regulations states that

"Before an administration notifies to the Bureau or brings into use a frequency assignment [...], it shall effect coordination, as required, with other administrations [...] for any station of a service for which the requirement to seek the agreement of other administrations is included in a footnote to the Table of Frequency Allocations referring to this provision." [10]

The meaning of this paragraph is that any administration can object to filings in these bands. The notifying administration has to seek agreement by any objecting administration. The objections against the use of the band do not necessitate technical reasons, it is enough to simply veto the use. Consequently, the filing in these bands takes long – if it is successful at all –, as can be seen in filings of the past years. Therefore it was identified in Resolution 659 that bands in which RR No. 9.21 applies are not feasible for short duration missions. However, since these bands are in general promising for short duration missions, it is proposed by many administrations that the requirement to seek agreement under RR. 9.21 is simply deleted from the Radio Regulations and with that make the band usable. It is currently being discussed if this is easily possible from a regulatory perspective (for the band 148–149.9 MHz). At the same time, new allocations in the Earth-to-space direction are being discussed (see next chapter).

In the downlink direction, several SOS allocations exist that are (theoretically) feasible for short duration missions. However, some constraints apply for these bands as well. The 137–138 MHz band is relatively low and with that antennas have to be large compared to the small satellite dimensions. On the other hand, the free space loss is low compared to UHF allocations. The secondary bands (267–272 MHz and 400.15–401 MHz) are not favorable as they do not provide protection against any primary services in these bands. The bands 267–272 MHz and 272–273 MHz are furthermore coordinated by governmental authorities in many countries, as they are so-called "North Atlantic Treaty Organization (NATO) harmonized bands". NATO uses these bands for various governmental systems and claims in study groups that avoidance of interference is of utmost importance. Therefore, use of these bands is difficult. The remaining band 401–402 MHz is heavily used by other services, including research satellite systems (e.g. data collecting systems) that require low level of disturbances from other satellites. Administrations therefore try to prevent additional use of these bands. The most favored band by administrations for use by SOS short duration missions is therefore the 137–138 MHz allocation. Still, as additional SOS allocations would unburden the existing allocations and since it was not clear from the beginning if the existing SOS allocations are feasible, it was examined whether new allocations for short duration missions in the bands 150.05–174 MHz or 400.15–420 MHz are feasible, as shown in the next chapter.

3.5 Sharing and compatibility studies below 1 GHz

Service	Frequency Band [MHz]
Fixed Systems	150.05–174; 406.1–420
Mobile Systems	150.05–174; 406.1–420
Radio Astronomy	153–154; 406.1–410
Global Maritime Distress and Safety System (GMDSS), AIS	156.2875–162.0375
Meteorological Aids	400.15–406
Meteorological-Satellite	400.15–403
SRS	400.15–401
SOS	401–402
EESS	401–403
COSPAS-SARSAT	406–406.1
SRS (space-to-space)	410–420

Table 3.6: Frequency allocations under study

Whenever potential new allocations are being investigated, the resistance of incumbent services is naturally high. This applies in particular to heavily used bands, while the resistance in formerly used bands is lower. The bands between 150.05–174 MHz and 400.15–420 MHz are used by a variety of services. A few applications are named in the following. Fixed systems are used for safety systems of air traffic control. Land-mobile systems are used for public safety agencies, utilities and transportation companies (including railway), during national emergencies, national disasters, aircraft distress, aircraft accident investigations and search and rescue activities. Additionally, land-mobile systems are used by governmental vehicles, hand-held devices and ships. Radio astronomy allocations exist in VHF and UHF and parts of the VHF band are allocated to GMDSS systems (ship, coast, satellite and aircraft). The lower UHF parts are used by research satellites and to a large extent by meteorological satellites and data collecting platforms, additionally a large portion is allocated to the use by Meteorological Aids systems (mainly radiosondes, but also rocketsondes and dropsondes). COSPAS-SARSAT systems are safety and rescue systems of high importance and have an exclusive allocation at 406–406.1 MHz. Manned stations have a wide-band (10 MHz) allocation between 410–420 MHz for SRS space-to-space links. Additional (regional) allocations are added in footnotes (e.g. for radio-location systems). A summary of all users (excluding allocations by footnotes) is given in table 3.6.

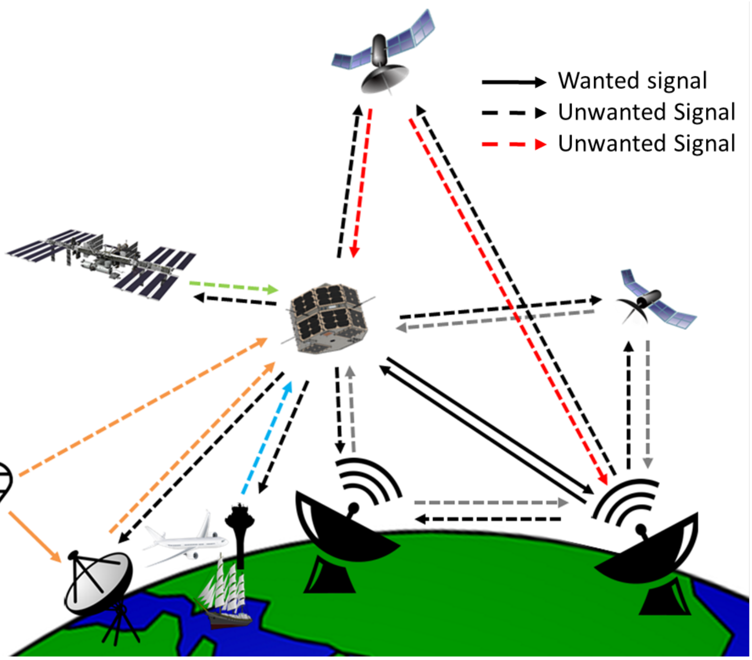

Figure 3.7: Different interference cases that need to be investigated as part of sharing and compatibility studies. The small satellite system in the center of the figure and the Earth station in the lower right depict the wanted signal, while other lines depict unwanted signals from or into other systems.

Compatibility and sharing studies had to be undertaken for all of these services. Compared to the simplified sharing basics in figure 3.1, the complex sharing scenario becomes more complicated, as seen in figure 3.7. The directions of interference stay the same, but the number of influenced systems in the wide frequency ranges that are mentioned above is increased significantly. The unwanted emissions have to be assessed for the following directions:

Unwanted emissions from short duration satellites and their Earth stations into:

- other NGSO and geostationary (GSO) satellites
- satellite Earth stations

- manned space stations (and astronauts during extravehicular activities)
- ground stations of radiosondes, dropsondes and rocketsondes
- mobile systems (aircraft, ship, vehicle, hand-held devices)
- fixed ground stations
- radio-astronomy stations

Unwanted emissions into short duration satellites and their Earth stations from:

- other NGSO and GSO satellites
- satellite Earth stations
- manned space stations (and astronauts during extravehicular activities)
- radiosondes, dropsondes and rocketsondes
- mobile systems (aircraft, ship, vehicle, hand-held devices)
- fixed ground stations
- radar stations

The protection criteria threshold for all studied systems are summarized in table 3.7. Whenever needed, the criteria that are defined in the applicable recommendations (e.g. I/N or pfd) have been converted to a pfd value. The methodology of the various sharing studies differed widely. As all studies were performed by different study group members, redundancy is frequent and some of the studies are extensive. The sharing study report [45] consists of approximately 250 pages. Capturing all details of this report would exceed the volume of this thesis, however the most important results on sharing feasibility are contained in table 3.8. In most bands, sharing on a co-channel basis is not feasible. Especially in the VHF range the protection criteria thresholds are significantly exceeded. The reason for this is that the protection criteria for all services have been set such that incumbent systems are protected as good as possible. Additionally, over the past decades, there have been many investigations into all bands, especially below 1 GHz; whenever there was scope for a new allocation, it was established and at the current time, almost all ranges are fully occupied. For the Met Aids band, mainly in the part where Met Aids do not coexist with other services, there have been controversial study results. Some studies yield that there is scope for a new SOS allocation, others yield that co-channel sharing is not possible. The prospect of success in these bands at

Service	Band	ITU-R Source	Station	Time (%)	Threshold	Unit
SOS	VHF	SA.363-5 [43]	ES	1	-166.7	dBW/kHz
SOS	UHF	SA.363-5 [43]	ES	1	-176.0	dBW/kHz
SRS manned	UHF	SA.609-2 [50]	ES	0.001	-178.0	dBW/kHz
RA	VHF	SA.769-2 [51]	ES	-	-234.9	dBW/kHz
RA	UHF	SA.769-2 [51]	ES	-	-238.9	dBW/kHz
Met Aids*	UHF	RS.1263-1** [52]	ES	0.02	-166.6	dBW/kHz
Met Aids*	UHF	RS.1263-1** [52]	ES	0.2	-174.3	dBW/kHz
Met Aids*	UHF	RS.1263-1** [52]	ES	20	-180.8	dBW/kHz
Met Aids*	UHF	RS.1263-1** [52]	ES	0.2	-179.1	dBW/kHz
SRS	UHF	SA.609-2 [50]	ES	0.1	-178.0	dBW/kHz
Radar (narrow)	any 1kHz	M.1461-2 [53]	ES	2000s integration	-208.2	dBW/kHz
Radar (wide)	any 1kHz	M.1461-2 [53]	ES	2000s integration	-171.6	dBW/kHz
LMS	VHF	M.1808 [54]	ES		-203.9	dBW/kHz
Fixed	UHF	F.758 [55]	ES	20	-175	dBW/kHz
EESS	UHF	SA.514 [56]	ES	1	-176.0	dBW/kHz
SOS	any 1kHz	SA.363-5 [43]	SS	1	20.0	C-I
SRS manned	UHF	SA.609-2 [50]	SS	0.1	-177.0	dBW/kHz
SRS	UHF	SA.609-2 [50]	SS	0.1	-177.0	dBW/kHz
EESS	UHF	SA.514 [56]	SS	0.1	-161	dBW/kHz
NGSO DCS	UHF	SA.2044 [57]	SS	1	-179.3	dBW/kHz
GSO DCS	UHF	SA.1163** [58]	SS	20	-177.4	dBW/kHz
GSO DCS	UHF	SA.1163** [58]	SS	0.1	-163.4	dBW/kHz

Table 3.7: Protection threshold criteria for different services and frequency bands. Remarks: ES (Earth station); SS (space station); *Met Aids (meteorological aids) values only applicable for radiosondes, additional thresholds apply for dropsondes and rocketsondes; **Recommendation currently under revision

Frequency band [MHz]	E-s	s-E	Remarks
150.05–174	No	No	
400.15–401	N/A	No	secondary s-E existing
401–402	No	N/A	primary s-E existing
402–403	No	No	
403–405	Yes/No	No	
405–406	No	No	
406–406.1	No	No	
406.1–420	No	No	

Table 3.8: Results of WP7B studies on feasibility of co-channel sharing with potential new SOS allocation in the Earth-to-space direction (E-s) and space-to-Earth direction (s-E)

WRC-19 is estimated to be low. The reason for this as well as the shortcomings of the studies will be explained in the next section.

3.6 Outcome of theoretical investigations and recommendations

Chapter 3 and a major part of the author's scientific research focused on theoretical investigations of spectrum use. The technical principles of frequency coordination and sharing studies have been introduced. The following subsection shall conclude the theoretical aspects, accompanied with a side glance on political aspects and shortcomings of frequency coordination and sharing.

3.6.1 Results of study work

Study group WP7B has investigated the required spectrum for short duration (or small satellite) mission TT&C and looked into existing SOS allocations as well as bands for potential future allocations. Although Resolution 659 invited to only look into potential new allocations if the existing allocations are not sufficient, sharing and compatibility studies in 150.05–174 MHz and 400.15–420 MHz were started early during the study cycle. The reason for this is that both proponents and opponents of short duration missions aimed to achieve study results in their favor as early as possible to defend their incumbent or new needs.

The first thing to note in the conducted studies is the fact that almost all studies used different methodologies for sharing analysis. During first meetings, general aspects for the studies were agreed on by the study group. Most of the study group members used these agreed parameters for their studies, however some did not. Even if the inputs to the studies are agreed, the methodology might change the results and in this, slight changes of parameters can result in few dB difference which might make a frequency range feasible or unfeasible. This was particularly evident in the study of Met Aids bands, where co-channel sharing was found to be feasible by some administrations (who are in favor of new allocations), while other administrations (who are against new allocations) found that sharing is unfeasible. There is no authority in ITU study groups that can reject a study if some of the parameters are not agreed. As a result, different studies on the same band with diverging outcome were included in the reports of the study group. Higher levels (in the last instance the WRC) will decide which of the study results is to be taken as more realistic.

An obvious shortcoming of all sharing studies is that only co-channel sharing is being investigated. A good example is the existing allocation for SRS in the space-to-space direction. This band is almost exclusively used for the ISS and nearby stations or astronauts during EVAs. A primary frequency of 414.2 MHz is typically used, an additional frequency of 417.1 MHz is used as backup. The rest of the large SRS allocation is unused (410–420 MHz). The SRS space-to-space allocation has high protection criteria thresholds, as the operation of manned space stations is critical and shall not be interfered in any case. For this reason, sharing was found not to be feasible. However, co-channel sharing studies do not take into account that some portion of the band might not be used at all. In general, an allocation around 419–420 MHz would not pose harmful interference to existing SRS systems, as there are no incumbent users. The same is valid for Met Aids bands. Radiosondes used to require large bandwidth per system (up to 300 kHz) and they are heavily used in many countries, especially in Europe (mainly Germany and France). However, new generation sondes only need about 6 kHz of bandwidth. Still the recommendations that are in-force claim protection for systems with a bandwidth of 300 kHz. The showstopper for SOS allocation in Met Aids bands will be the protection criteria for rocketsondes and dropsondes, which are very rarely used. In practice, they could be simply operated in another portion of the large Met Aids band (400.15–406 MHz) and would potentially never experience interference from a short duration mission. To conclude this matter, sharing studies that only take into account co-channel sharing cannot reveal the whole truth about sharing feasibility.

Although the study group did not come to a conclusion that is satisfying for all parties, proposals (or methods) have to be sent to the WRC how to answer the study question. There is always a method A which proposes "No Change" to the existing regulations. A second solution was drafted as method B, in which the existing allocation of 137–138 MHz is recommended for the space-to-Earth direction, while the band 148–149.9 MHz is proposed to be used in the Earth-to-space direction, if (and only if) RR No. 9.21 can be removed from this band. It is currently being investigated whether No. 9.21 can be simply removed from this band and whether administrations world-wide have objections against this change. The third method C proposes to use 137–138 MHz for the space-to-Earth direction and a portion of the Met Aids band (either 403–404 MHz or 404–405 MHz) for the Earth-to-space direction. As this band is highly used by strong administrations, it is the least likely option.

Nevertheless, any other outcome of the study question under WRC-19 Agenda Item 1.7 is possible, as well. The WRC has the right to overrule any recommendations by the study groups. If it is decided by consensus that some portion of 150.05–174 MHz or 400.15–420 MHz is not needed anymore by any incumbent user, the conference can reallocate a part of these bands. Sometimes agenda items are used in negotiations: If administration A agrees to administration B's proposal under one agenda item, administration B will support administration A under another agenda item. During the last days of a WRC, decisions become purely political and the technical results lose importance. There is one specific agenda item that might become important during these negotiations and that will definitely have an impact on small satellites, which will be discussed in the next section.

3.6.2 Other impacts on small satellite TT&C

In the past years, it was identified that some Earth stations of small satellites create harmful interference to systems in the bands 399.9–400.05 MHz and 401–403 MHz. These bands are historically mainly used by Data Collection Systems (DCS) which have low-power transmitters on the ground and high gain antennas on their space stations. Small satellites work in the opposite way: The Earth stations use high power, while the satellites have low gain antennas. This leads to the problem that DCS systems cannot receive data anymore if Earth stations of small satellites are present. Therefore, WRC-15 decided to look into these bands and to decide whether power limits can be introduced under WRC-19 agenda item 1.2 [59]. An EIRP of 7 dBW for EESS systems is under discussion which will in effect make the bands unusable for small satellites. The small satellite community has not put great effort in this agenda item, as opponents in these bands are basically all space administrations and scope for success is low. However, this agenda item might become part of the political negotiations ("If administration A supports agenda item 1.2, administration B will support agenda item 1.7").

At the same time, more and more companies file (small satellite) mega-constellations. OneWeb and SpaceX with their hundreds and thousands of satellites are only the largest player to name, but there are several companies that filed or plan to file constellations with at least tens of satellites (Planet, O3b, Spire, LeoSat and more). Administrations fear that any new allocation for short duration missions might be misused by these constellations, making the band in practice unusable for other systems. The spectrum demands of constellations will affect all satellite systems, small satellites with short duration missions included.

3.6.3 Recommendation for future work

The outcome of the studies under WRC-19 agenda item 1.2 and 1.7 is still open. Whether the bands will be used at all can also only be seen when or if new allocations become available. As a questionnaire among small satellite developers (conducted by the author of this work) has shown, developers prefer to use UHF bands for TT&C rather than VHF bands. Most operators stated that in future, higher bands would most likely be used. With the rapid advances in technology, this future might become presence before regulatory changes are introduced for small satellites in the lower bands.

Additionally, the current way of coordination between space systems seems to be fallen behind technological progress. NGSO systems have highly dynamic orbits and link times are difficult to plan in advances, as orbit parameters change. A typical coordination between administrations includes coordination using the Local Time of Ascending Node (LTAN). If the LTAN of two systems is different, sharing of a frequency is possible and filings are completed. However, often small satellites move from one launch vehicle to another, with the effect of different LTAN or completely different orbits. A timely coordination of these modifications is eventually not possible.

Current communication systems, especially those introducing software defined radio (SDR) technology, have the functionality of using frequency channels inside a defined bandwidth on a dynamic basis. Dynamic frequency management or cognitive radio are buzzwords of these technologies and they have proven to be efficient in terrestrial telecommunication and wireless systems [60]. Satellite systems are still very conservative and developers do not want to rely on algorithms to choose the frequency channels to use. However, changing from traditional ways of coordination to a self-coordinated procedure would ease up the coordination work significantly and unburden existing allocations.

The remaining unsolved issue is the fact that modifications of the use of allocations is negotiated based on the stated use of the bands. Operators tend to exaggerate when asked about the utilized capacity of their bands. Additionally, some operators use bands that they did not file their system for. Some operators do not even file all their used channels at all. This can result in harmful interference. There are many terrestrial solutions to detect the current use and potential harmful interference on the ground. However, these systems cannot evaluate the dynamic use of spectrum in space. Therefore, two systems for spectrum analysis from orbit have been designed, which shall be explained in the following chapter.

4 Implementation of spectrum analysis missions

This chapter deals with on-orbit spectrum analysis missions. After an introduction on the necessity of spectrum analysis from orbit, the subsequent chapters briefly depicts the basics of spectrum analysis, followed by general mission concepts and applications for spectrum analysis. Section 4.4 and 4.5 introduce two hardware implementations of the above-mentioned mission concepts, of which one (MarconISSta) already revealed first on-orbit results, while the other (SALSA/SALSAT) represents part of the on-going and future efforts at TU Berlin to improve the global frequency sharing scenario.

4.1 Introduction

As explained in earlier chapters, the paperwork on frequency coordination cannot reflect the real environment of spectrum use and interference events. Terrestrial spectrum analyzers can investigate local use and identify local interferer, however they cannot investigate the situation in orbit. Various issues have been reported in the UHF amateur-satellite bands where satellite developers experienced interference on their satellite systems, while no interference could be measured on the ground. Long-term observations yielded that the satellites received signals without problems when the satellite was in certain azimuth directions of the ground station, while in other directions the satellites did not respond to telecommands. This led to the speculation that there is a terrestrial interference that transmits in the space direction with sufficient power that the satellite cannot recognize the signal from its corresponding ground station and for this reason did not respond anymore. This behavior was recognized by Prof. Renner at TU Berlin for his TUBSAT satellites, starting from approximately 2014. An unexplainable observation however was that this behavior could not be observed for the newer BEESAT satellites. Other research groups identified the source of the interference: Agalet et al. revealed that there is a strong, pulsed interference in the Northern hemisphere [61]. It was later identified as a radar system in the United Kingdom that was (re)activated in 2013 for space object tracking. The operation of this radar system is in line with the Radio Regulations, since radiolocation is a primary service in this band

and the transmissions follow ITU-R Recommendation M.1462 [62]. Busch et al. performed a study on UHF band usage and provide similar findings [63]. The reason why some satellites were interfered, while others worked nominally, are the characteristics of the radar emissions and the satellites' communication systems. The radar emissions are comparatively strong (up to 5 MW), but short in time (0.25 ms to 16 ms). Satellites with Forward Error Correction (FEC) methods integrated in their communication systems (like the BEESAT series) can correct disturbances by pulsed signals, while satellites without FEC are disturbed.

Agalet et al. and Busch et al. performed their study on a point-by-point basis. Both groups used the Received Signal Strength Indication (RSSI) level on different predefined frequencies to identify interferers and the general usage of frequency channels over time. The studies resulted in meaningful heatmaps for these channels. However, the dataset is limited by the fact that only few channels could be investigated. A spectrum analysis over a wider range can increase the data base significantly. Various research groups have therefore looked into spectrum analyzer payloads for satellite applications and different systems will be launched in the upcoming years (SIGINT payload [64], FMP [65], HawkEye360 [66, 67], OPS-SAT [68]). The research group at TU Berlin has developed two approaches for spectrum analysis that will be introduced in the subsequent chapters. To provide a technical background, the next section will summarize the basics of spectrum analysis.

4.2 Basics of spectrum analysis

This section introduces the basics that are needed to understand the spectrum analysis methods explained in the subsequent sections. It is intended to explain the background that is needed to describe the on-orbit spectrum analysis payload's functionality. Various textbooks explain the topic of spectrum analysis in more detail (e.g. [69]).

4.2.1 Fourier transform

A sine wave is defined by its amplitude A, frequency f and phase φ_0 as follows:

$$s(t) = A \cdot sin(2\pi f\ t + \varphi_0) \tag{4.1}$$

where the frequency f for the case of electromagnetic waves is defined as $f = \frac{c}{\lambda}$ with the vacuum speed of light c and the wavelength of the signal λ. Signals can be described as a superposition of multiple sine waves:

$$x(t) = A_0 + \sum_{i=1}^{N} A_i \cdot sin(2\pi f_i \; t + \varphi_{0,i}) \tag{4.2}$$

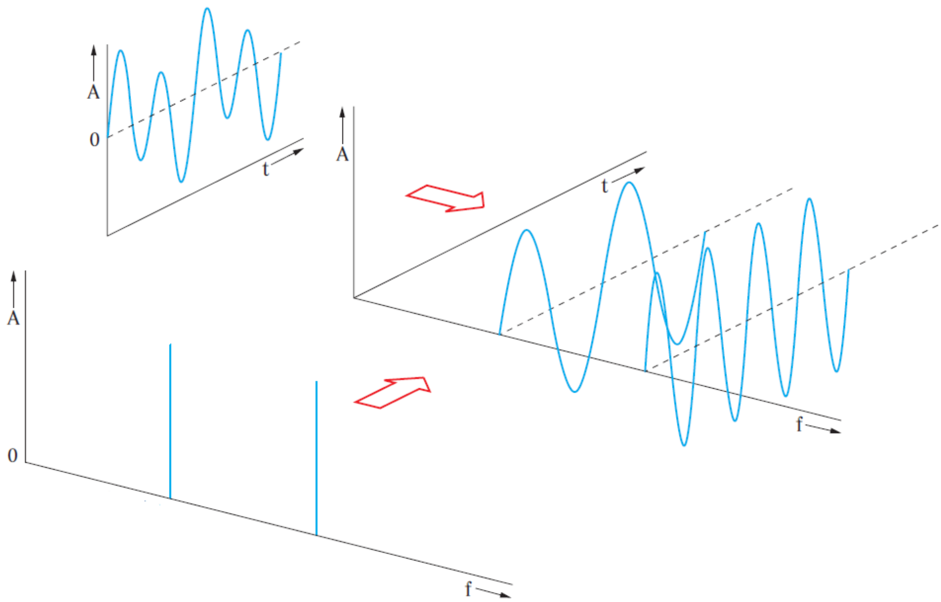

Figure 4.1: A signal divided into its integral frequency parts (adapted from [69])

Since variation of amplitude, frequency and phase are used in satellite communication to transport (or modulate) information on carrier waves, the disassembly of signals into their different spectral components is desired (see figure 4.1). The mathematical tool for this process is spectrum analysis.

The mathematical operation to divide a signal into its integral components is called Fourier transform:

$$X(f) = \frac{1}{2\pi} \int_{-\infty}^{\infty} x(t) e^{-2\pi i f t} dt \tag{4.3}$$

In discrete systems, as in most digital signal processing applications, discrete fourier transform (DFT) is used. The most widely used algorithm for computing the DFT is called fast fourier transform (FFT). The details of this algorithm do not add to the scope of this work, however various parameter that influence the performance of the FFT shall be introduced in the following sections. Prior to this, it shall be explained how the input parameters to the FFT, namely the samples of the signal, are created.

Receiver and signal processor

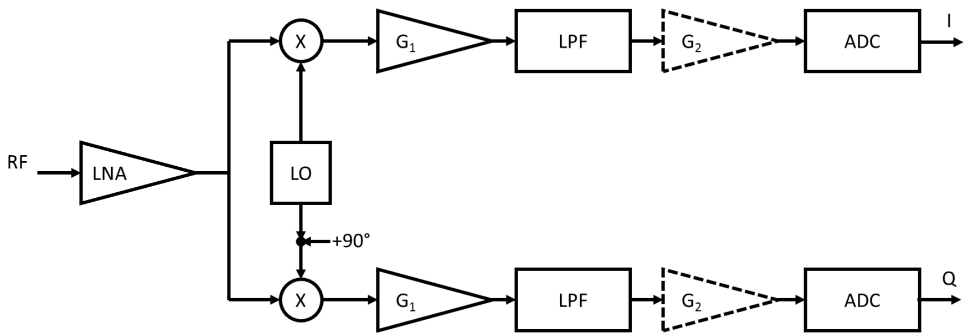

Figure 4.2: Modern receiver architecture (adapted from [70])

Figure 4.2 depicts the architecture of modern receivers [70]. The RF signals that are received contain the information modulated on a HF carrier, which for satellite systems has a center frequency in the MHz or GHz range. After the RF signal is received, it is amplified by a Low Noise Amplifier (LNA) to minimize the influence of additional noise in the subsequent filter and receiving elements. In a next step, the signal is mixed with a Local Oscillator (LO) signal. Mixing two signals with frequencies f_1 and f_2 results in two signals with frequencies $f_1 - f_2$ and $f_2 - f_1$. If the LO signal has a frequency close to the center frequency of the RF carrier, the information that was modulated on the carrier can be retrieved from $f_1 - f_2$

and processed in following steps. After (optional) additional gain elements, the signal which is now in its base band is low-pass filtered in order to remove all high-frequency parts of the signal. With only the relevant information left on the signal, it is now converted into discrete values using an Analog-to-Digital (AD) converter (ADC). However, RF signals consist of a real and an imaginary component (called Q and I part in digital signal processing). This method would only digitize one of these parts. To retrieve both parts, the signal has to be mixed twice: Once using the original LO signal and additionally (on a different path) using the LO signal phase-shifted by 90 degrees. This will result in two digitized signals: I and Q. The two signals provide great advantages in communication theory, as they provide additional information on the phase of a signal and modulation techniques with higher symbol rates can be used. For spectrum analysis, I and Q provide the advantage that the doubled number of signals in effect doubles the bandwidth of the receiver. The Shannon theorem [71] states that the sample rate has to be double the size of the largest detectable frequency. However, since I and Q provide independent information on the signal, the sample rate and the largest detectable frequency become the same.

FFT parameter

The following paragraphs introduce the main parameters of FFT algorithms. Again, further literature is recommmended for deeper background, e.g. [69].

Sample rate

The sample rate R defines the number of samples that are taken per second. In consequence, as explained in the previous chapter, it defines the bandwidth which can be observed. If the carrier frequency is 435 MHz and the sample rate is 10 MHz, the range 430–440 MHz can be investigated.

FFT bins

The FFT bins are the number of frequency sub-ranges (or bins) into which a bandwidth is subdivided. For computational reasons it is beneficial to choose values that are a power of 2 (2^N), commonly 512, 1024, 2048 or 4096. An FFT bin size of 512 depicts that 512 frequency values result from the FFT calculation.

Bandwidth Resolution

The Bandwidth resolution (RBW) defines the bandwidth (or size) of each bin and can be derived from sample rate and the number of fft bins $N_{FFTbins}$:

$$RBW = \frac{R}{N_{FFTbins}} \tag{4.4}$$

If a signal is sampled with a rate of 1 MHz and the FFT consists of 512 bins, the RBW is 1.95 kHz.

Windowing

Before an FFT is performed, the signal is cut into consecutive blocks. This process is called windowing. If no special window form is used (so-called rectangular window), a side-effect of windowing are the abrupt cuts at the beginning and end of each block which result in significant side-lobes next to the real signal. Advanced window forms (e.g. Hamming, Hann, Blackman-Harris) can be used to reduce these side-lobes. The window forms vary in peak value and bandwidth of main-lobe and side-lobes.

Averaging

When the FFT is performed at the same rate as the data is sampled, a giant amount of data is created. It is often sufficient to only store some of the data over a certain period of time. For example, if a signal is monitored that only changes slowly over time, high sample rates are not needed. In that case, it would be sufficient to only store the average over a certain timespan. Another widely-used method is to only store the maximum (peak) values over a period of time, significantly reducing the size of required storage.

4.3 Mission concepts

Using an FFT or other spectrum analysis algorithms, investigations of wide frequency spectra are possible. Depending on hardware capabilities, modern spectrum analyzers can measure the RSSI over various MHz of bandwidth. The drivers that define mission concepts for spectrum analysis are the satellite orbit and the antennas, as described in the following.

4.3.1 Satellite orbit

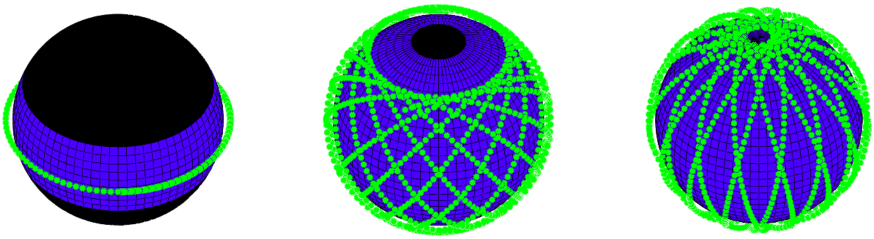

Figure 4.3: Global coverage using omnidirectional antennas after 24 hours for inclination angles of 0° (left), 51.6° (middle) and 99.7° (right). Blue highlighted areas are covered by the measurements, while black areas are not covered.

The satellite orbit defines the spatial coverage of the measurements. For obvious reasons the inclination strongly influences the regions that can be investigated (see figure 4.3). Only polar orbiting satellites can cover all areas, irrespectively of the used antennas. Satellites with lower inclination have the advantage to revisit regions of interest more frequently. If global coverage is desired, the desired orbit would be polar. Even though many launchers target a Sun-synchronous orbit, it would be disadvantageous to choose this orbit, since local coverage would be fixed regarding time. Time-independent measurements would not be possible. At the same time, it is highly probably that other satellites have synchronous orbits and influence the measurement results. An orbit that is as independent as possible from other satellites should be desired.

4.3.2 Antennas

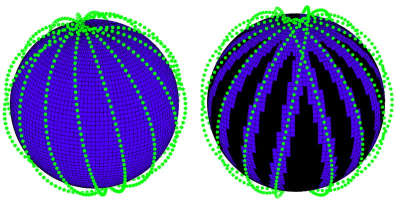

Figure 4.4: Coverage of an SSO satellite with different antenna beam widths after 12 hours. Left: omnidirectional; Right: 90°.

The antennas and specifically the beam width of the antennas influence the time until global coverage can be achieved. Omnidirectional antennas transmit and receive electromagnetic waves into and from all directions with the same strength. Highly directional antennas have an increased gain in the direction into which the antenna is pointed, however information from other directions is lost. If a satellite antenna is used for reception of terrestrial signals, the regional coverage (foot print) is influenced by the antenna's directivity. Figure 4.4 depicts the two cases of an omnidirectional antenna and an antenna with 90 ° beam width after 12 hours of measurement time. It can be clearly seen that more time is needed to achieve global coverage. Figure 4.5 depicts the coverage of the latter example over time.

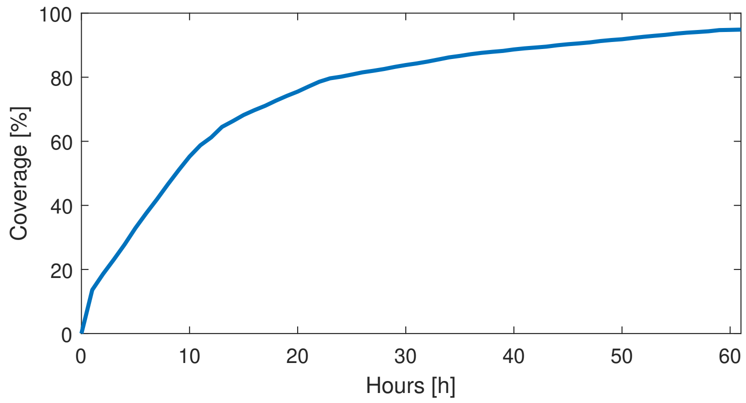

Figure 4.5: Spatial coverage over time (beam width: 90 °)

4.3.3 Coverage analysis

Over time, an assessment of the global use of spectrum can be assessed. The recorded data can be analyzed in various ways, of which heat maps are of high interest. A heat map visualizes the global use of a frequency (or frequency channel). Figure 4.6 shows a fictional example of a heat map that is based on an ISS orbit. The level of signal strength (the "heat") defines the intensity of a color (in this example *red*) based on a predefined color bar. The resulting map visualizes areas of high frequency (channel) use. The signal strength can be either the maximum value of all measurements over this region or an average of a predefined time-span. If enough data is available, even the global use of bands for different times of a day can be assessed.

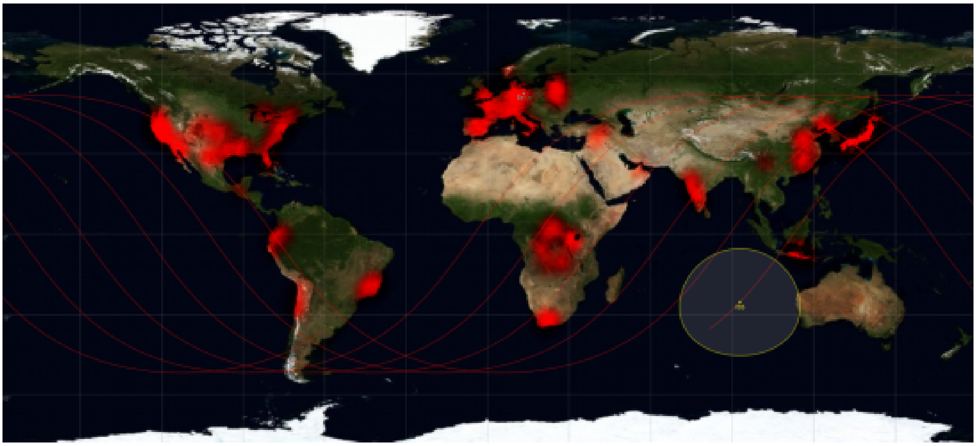

Figure 4.6: Artist's impression of frequency use, visualized as heat map [72]. Red areas denote areas of high received signal levels.

4.3.4 Interferer localization

A second use case for orbiting spectrum analyzers is the localization of terrestrial interferers. The easiest way to identify terrestrial signal sources is to observe an area over various passes. The received signal strength P_r is based on the transmitter's RF output power P_t, the gains of transmitter G_t and receiver G_r and the path losses L_p:

$$P_r = P_t + G_t - L_p + G_r \tag{4.5}$$

If the gains and output power are assumed to be (quasi-)constant, the path loss is the biggest influence. Since the slant range between source and spectrum analyzer is different during different passes, the source can be localized. Since the gains in most cases will not be constant, several passes are still needed to identify the source of interference.

A more sophisticated method for interferer localization is to include spectral information in the analysis. It is a well-known fact that the frequency of a signal is shifted if source and sink are in relative motion to each other. The relation between a moving receiver's frequency f_r and a fixed transmitter's frequency f_t is given as

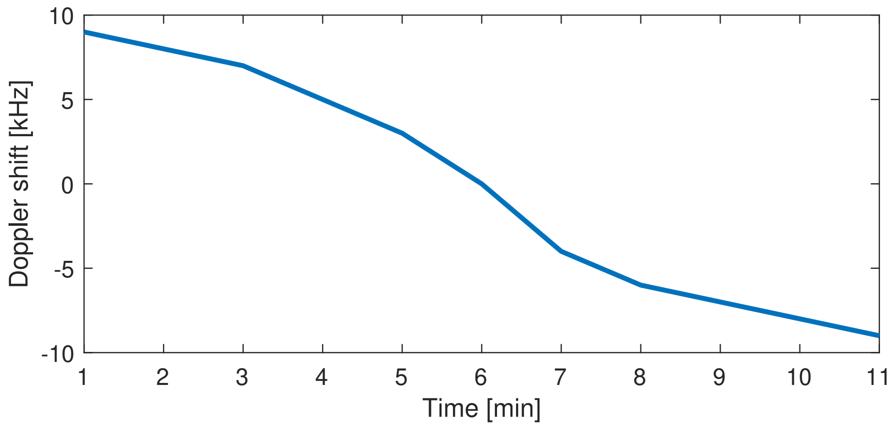

Figure 4.7: Doppler shift for UHF signal

$$f_r = f_t \ (1 - \frac{v(t) \ r_{si}(t)}{c \ |r_{si}(t)|}) \tag{4.6}$$

where $v(t)$ is the receiver's relative velocity, r_{si} is the distance between source and interferer and c is the speed of light.

Figure 4.7 shows the shift of a UHF signal over the time of one satellite pass. Lopez et al. use this equation to track the location of terrestrial platforms of the ARGOS system [73]. For most satellite systems it can be assumed that the satellite velocity and position are known from Two Line Element (TLE) data, retro-reflectors or GPS data. Additionally it can be assumed that the altitude of the terrestrial transmitter is known to a certain extent. Although the Earth radius is not globally constant, the deviation from the commonly used value of 6378 km is not more than 30 km in any area. The remaining unknowns are the longitude and lattitude of the signal source's location as well as the transmitting frequency. The transmitting frequency can be derived by analyzing figure 4.7. If enough samples are available, it can be derived as the center value between the maximum and minimum Doppler shift. The accuracy can be further improved by finding the maximum change of frequency (the derivative of the Doppler shift) which occurs when transmitting frequency and receiving frequency are the same. If omnidirectional antennas are used, this coincides with the time when the received signal strength reaches its maximum.

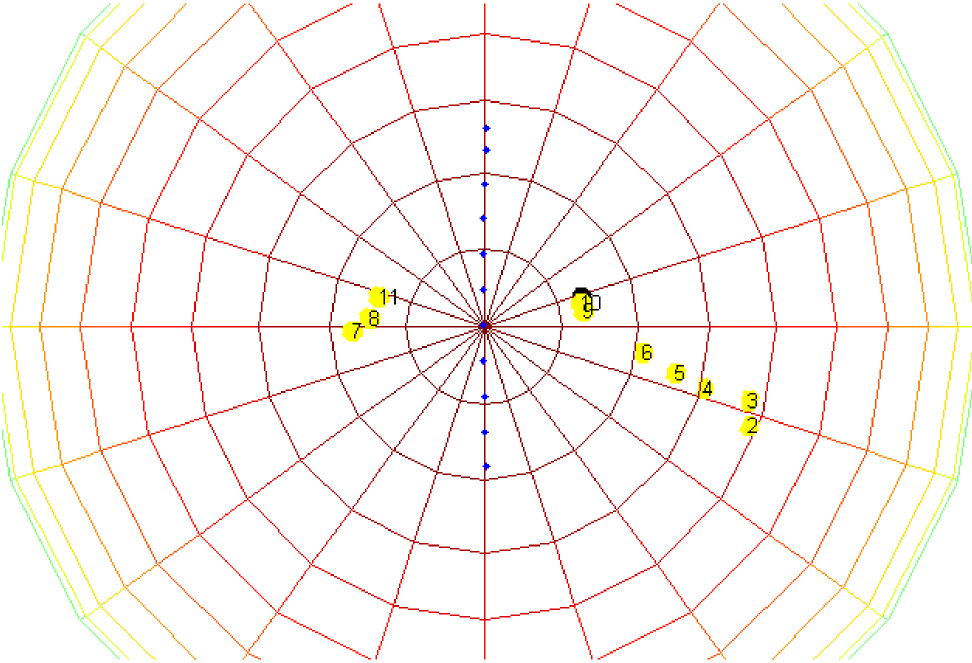

Figure 4.8: Interference detection using one pass only

Figure 4.8 shows the results of an algorithm to localize a signal source. In this example, a polar orbiting satellite is the receiver and a station in the polar region is the transmitting source (black dot). The blue points represent locations on which measurements were taken during a spectrum analyzer's pass over the region. The time resolution is one minute, eleven measurements are taken. The minimum number of required measurements is two. The first five solutions are comparatively far away from the signal source. The high distance from the real location can be explained by the fact that the derivation of the transmitting frequency is poor for the first measurements. Only after the Doppler shift changes from a positive to a negative value, the transmitting frequency can be calculated more precisely. The localization keeps improving until the solution is very close to the real location after taking nine and ten measurements into account. However, after taking all eleven measurements into account, the calculated solution "jumps" to the other side of the satellite's path. The reason for this is that the equation has two solutions, one on each site of the satellite's path. This also explains the results after seven and eight measurements.

The only way to find one distinct solution for the case of omnidirectional antennas is to include a second pass of the satellite. Since the path of the satellite changes, the slant range from the transmitting source changes as well. While the solution based on one pass had two symmetric solutions, including more measurements from an additional pass makes the set of equations assymetric and with that distinct. As can be seen in figure 4.9, the correct solution is found if twelve or more measurement points are taking into account.

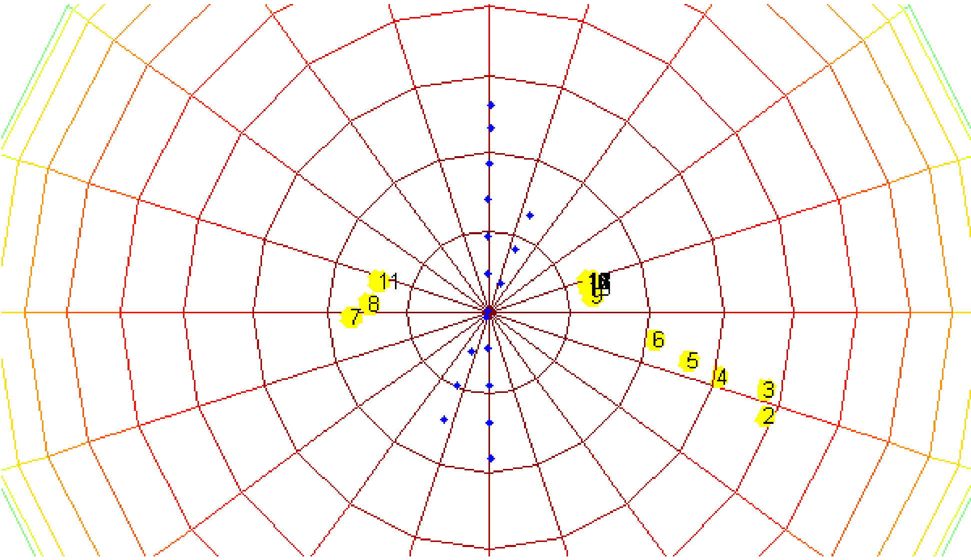

Figure 4.9: Interference detection using two passes

If the antennas are not completely omnidirectional, like it is the case for almost every application, a well-chosen orientation of the antenna allows distinct solutions to the equation even after one satellite pass. Figure 4.10 shows four different passes of a satellite over a certain region. Again, a black dot denotes the signal source. During two passes (1) and (2) the satellite passes the terrestrial signal source on the left side, while during the other two passes (3) and (4) the satellite passes on the right side. The passes (2) and (3) are much closer to the signal source than the passes (1) and (4).

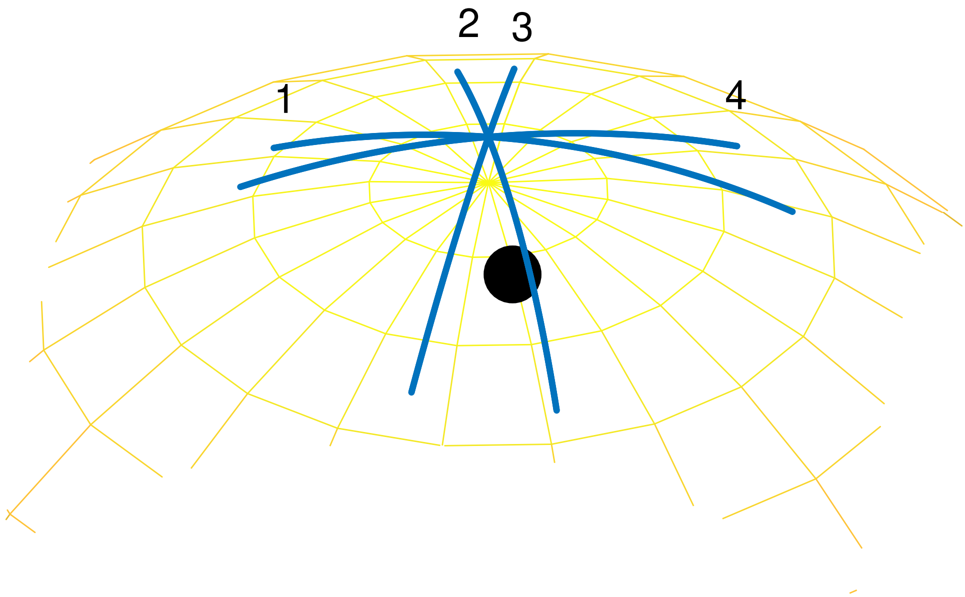

Figure 4.10: Four satellite passes and a signal source (black circle). The flight direction of the satellite for each of the passes is from the position where the orbit is marked (1, 2, 3, 4) towards the unmarked side.

The influence of the radiation pattern shall be shown at the example of a dipole antenna. Dipole antennas, as they are used by most small satellites below 1 GHz, have a so-called "donut-shaped" radiation pattern. While the radiation is symmetrical in all azimuth directions, the signal strength varies in elevation. There is almost no gain in the direction into which the rod of the antenna is pointing, which leads to the donut shape of the radiation pattern. Figure 4.11 shows four different orientations of such an antenna on a satellite: in configuration a) the antenna is pointing in nadir direction, accordingly, the direction of lowest gain ("donut hole") is pointing towards Earth. In configuration b) the antenna is pointing in flight direction, while in configuration c) the antenna is pointing 90 ° to the right side of flight direction (orthogonal to Nadir and flight for a circular orbit). In configuration d) the antenna is pointing 45 ° to the right side of flight direction (forward-right direction).

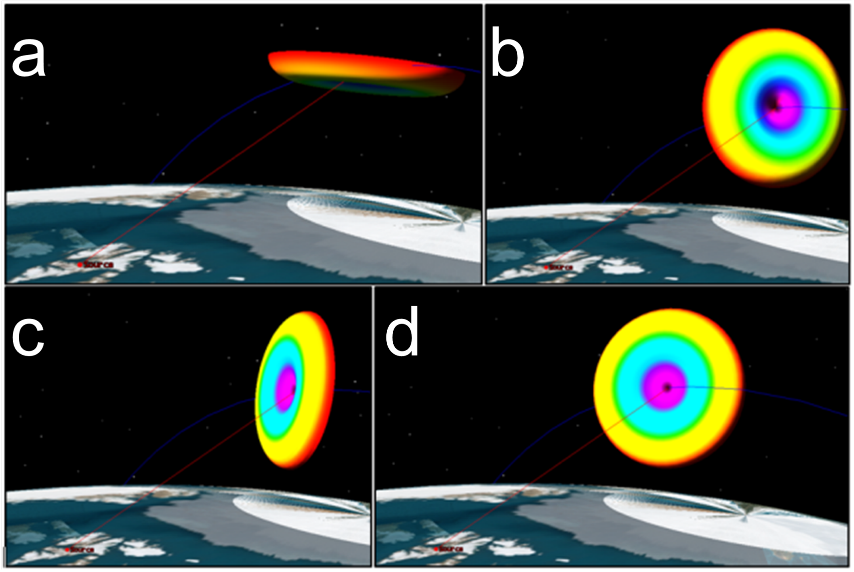

Figure 4.11: Four different orientations of a monopole antenna on a satellite. a) nadir pointing b) in flight direction c) pointing 90 ° to the right side of flight direction d) pointing 45 ° to the right side of flight direction.

The influence of the different orientations is shown in figure 4.12. The figure shows four satellite passes, separated by vertical solid lines, for four different antenna orientations (a-d). The vertical dashed lines show the point of shortest distance of signal source and satellite during each pass. In the case of Nadir antenna orientation (case a) the received signal strength rises as the satellite approaches the signal source for each of the passes except pass 2. As can be seen in figure 4.10, the satellite passes the signal source at a high elevation of almost 90 ° during pass 2. This makes it pass through the area of the lowest gain. The low gain explains the decrease of received signal strength during pass 2. This behavior does not occur for the forward antenna orientation (case b), since the radiation pattern is symmetrical at the point of shortest distance for all passes. For the right side case (case c), the gain is lower for higher distances as the antenna rod points into the direction of interference. The most interesting behavior can be seen in the case of an asymmetrical orientation of the antenna (case d). The highest gain does not coincide with the shortest distance for all four passes. During passes 1 and 2 the signal strength is at its maximum after the shortest distance has passed, while during passes 3 and 4 the maximum is reached before the shortest distance has passed. This can be used to identify from which side the interference originates. Since passes 1 and 2 are to the left of the source and passes 3 and 4 are to its right, it can be concluded that for passes on the left of a source, the maximum occurs after the shortest distance has passed for the case of a "forward-right" oriented antenna. This analysis makes distinct solutions for signal localization possible, using only one satellite pass.

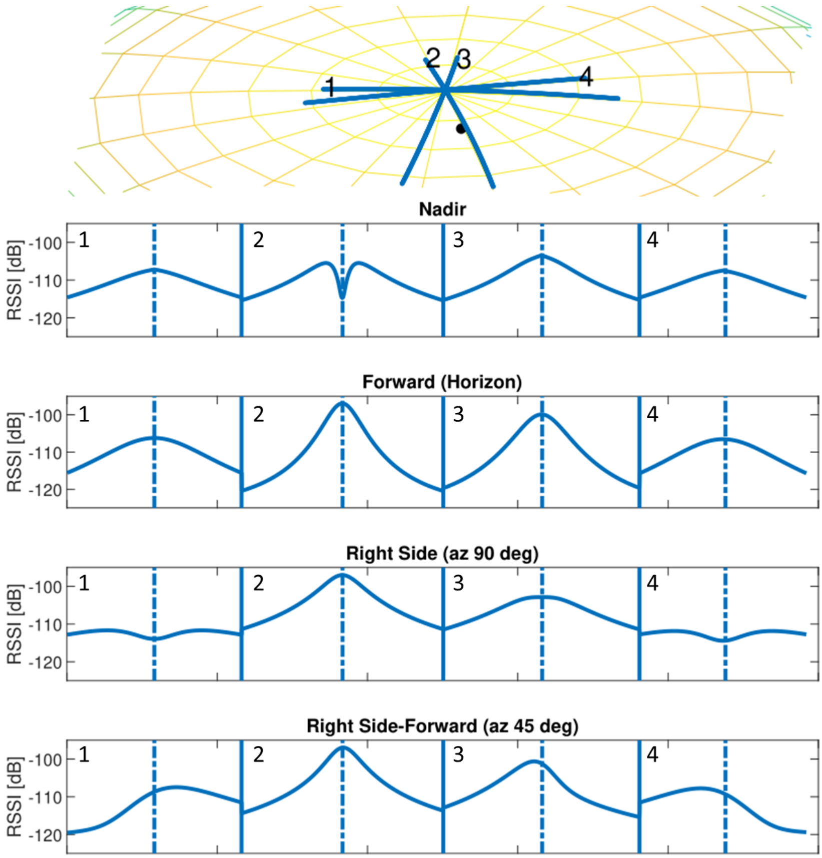

Figure 4.12: Signal strength for 4 different antenna orientations over 4 satellite passes: a) nadir b) forward c) right side of flight and d) 45 ° to the right side of flight. The dashed vertical lines highlight the closes distance between satellite and source during each pass.

4.3.5 Conclusion for mission concepts

In conclusion, two applications for spectrum analysis are of interest: analysis of the global use of spectrum and identification and localization of signal sources. Both concepts can be driven by the same hardware elements:

– antenna(s)

– RF analog circuits for signal detection and filtering

– LO for demodulation of signals

– fast AD converter for digitization of signals

– processing unit for FFT (plus working memory)

– payload control unit/ payload data handling

– storage/ memory

The following two sections will introduce two implementations of the mission concepts: MarconISSta and SALSA [74]. Both implementations are based on the COTS SDR LimeSDR from Lime Microsystems [75]. Although SALSA is the original project from which MarconISSta was derived, the section on MarconISSta will be introduced first. MarconISSta uses a LimeSDR on the ISS without hardware modifications. The section on SALSA will build up on the before-mentioned and introduce the modifications needed for a satellite payload.

4.4 MarconISSta

MarconISSta (from marconista, Italian for radio operator) is a spectrum analyzer experiment which is part of the ESA Horizons mission. It uses existing amateur radio antennas outboard the ESA Columbus module to which a COTS SDR called LimeSDR is connected. This USB device is connected to a Single Board Computer (SBC), which preprocesses and stores the data. During defined commanding windows the data is downlinked via the ISS Ku band antennas. MarconISSta was developed during a time-span of approximately one year between kick-off and delivery. The development team at TU Berlin was led by the author, supported by a student team that assisted in design and verification processes on a voluntary, non-paid basis, besides the regular coursework.

This section will provide background on the origins of MarconISSta, the requirements, design and development process. The verification process will be documented as well as first flight results.

4.4.1 Background

The considerations on a spectrum analysis satellite payload at TU Berlin began as early as 2013. The first DLR funded project on the topic was initiated in October 2016 (grant no. 50 YB 1635). The project called SALSA aimed at the development of a spectrum analyzer payload prototype. Additionally, concepts for integration into potential satellite buses were investigated. This work was partly conducted in lectures given by the author. Besides integration into the TU Berlin satellite bus systems, the idea of integrating a spectrum analyzer as an internal payload aboard the ISS arose and was included in the subsequent project work. Development of ISS payloads is generally complex, time-consuming and extensive in safety and security processes. However, if certain conditions are met, integration becomes feasible even in a short development cycle, as shall be shown in the following.

In the beginning of 2017, DLR and ESA were looking for German experiments to be included in the ESA Horizons mission, during which ESA astronaut Alexander Gerst would spent his second stay aboard the ISS. First contact with responsible staff at DLR was established in January 2018. After initial conversations with representatives of DLR and ESA it has been agreed to include MarconISSta under the premise that all deadlines can be met. Hardware and verification process were paid by TU Berlin, while DLR would raise the funds for launch, operations and crew time. As MarconISSta makes use of the amateur radio antennas outboard the Columbus module, agreement and cooperation of ARISS was needed as well. Technical support by ARISS members was provided from the kick-off of MarconISSta and official ARISS approval was achieved in October 2017.

4.4.2 Hardware concept

The original hardware concept is depicted in figure 4.13. The spectrum is assessed via amateur radio antennas. There would be a number of interesting frequency bands to be observed, however the choice of bands is dependent on the available antennas. Since the ARISS antennas are the only ones available, MarconISSta focuses on amateur-satellite bands in VHF, UHF, L and S band.

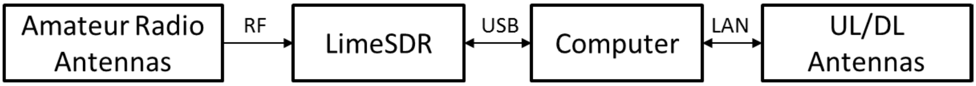

Figure 4.13: Original hardware concept for MarconISSta. The spectrum is assessed via amateur radio antennas. The LimeSDR receives, filters and digitizes the signals and forwards them to a computer. The computer stores the data and downlinks them via the station LAN and ISS Ku band antennas. New experiment parameters are uplinked via the same antennas.

A LimeSDR is chosen to receive, filter and digitize the data. Figure 4.14 shows the hardware. The core component of the LimeSDR is a field programmable RF chip called LMS7002M [76]. The chip offers two input channels (RX) and two output channels (TX). It covers the range from 100 kHz to 3.8 GHz, can sample with up to 160 MHz and discretize signals with 12 bit. In figure 4.14 the LMS7002M can be seen on the left side, which is the HF part of the board, as the center element. The other components of the HF part are analog circuits from and to six input (RX, three per channel) and four output (TX, two per channel) antenna connectors. The reason for multiple input and output channels is to optimize reception and transmission for different frequency ranges. More precisely, the three inputs per channels are optimized for low frequencies (0.1–2000 MHz, narrowband), wide frequencies (0.1–3800 MHz, broadband) and high frequencies (0.1–3800 MHz, narrowband). It should be noted that Lime Microsystems identified hardware issues with the reception below 1 GHz and the board that was used for MarconISSta is adapted in a way that both low and wide input port use the same components, such that they in effect are tuned for the same frequency range, with the best matching below 1 GHz. The left part of the board consists of an FPGA (Altera Cyclone IV), a Ultra Serial Bus (USB) 3.0 controller (Cyclone CYUSB3014), DDR2 SD-RAM working storage and additional peripherals to support the main components.

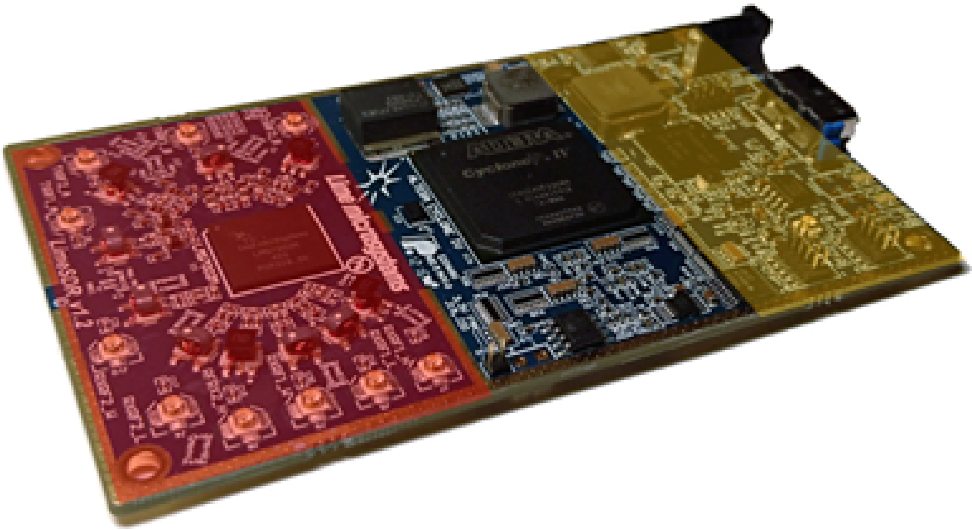

Figure 4.14: Lime Microsystems LimeSDR [77]. The left part (red highlight) represents the HF circuitry, including the LMS7002 transceiver chip, analog circuits and RF connectors. The middle part includes the Altera Cyclone IV FPGA (center element), the right part (orange highlight) shows USB 3.0 microcontroller and various peripheral components.

The block diagram is depicted in figure 4.15. Although the LimeSDR can transmit and receive RF signals, only the receiver functionality is needed for MarconISSta. The transmitter is only internally used for calibration processes. After the receiving unit amplified, mixed and filtered the received signals, they are digitized and pre-processed using an integrated signal processor. A USB microcontroller controls the device and forwards the data.

A computer is used to connect and control the LimeSDR, start new experiment runs, store the received data and forward it to ground. At the initiation of the project it was not yet defined which kind of computer shall be used, however it was proposed to use a SBC like a Raspberry Pi computer [78]. SBC are small, light-weight and consume little power. USB devices can be connected and a LAN connection is available to connect the system to the Joint Station LAN (JSL).

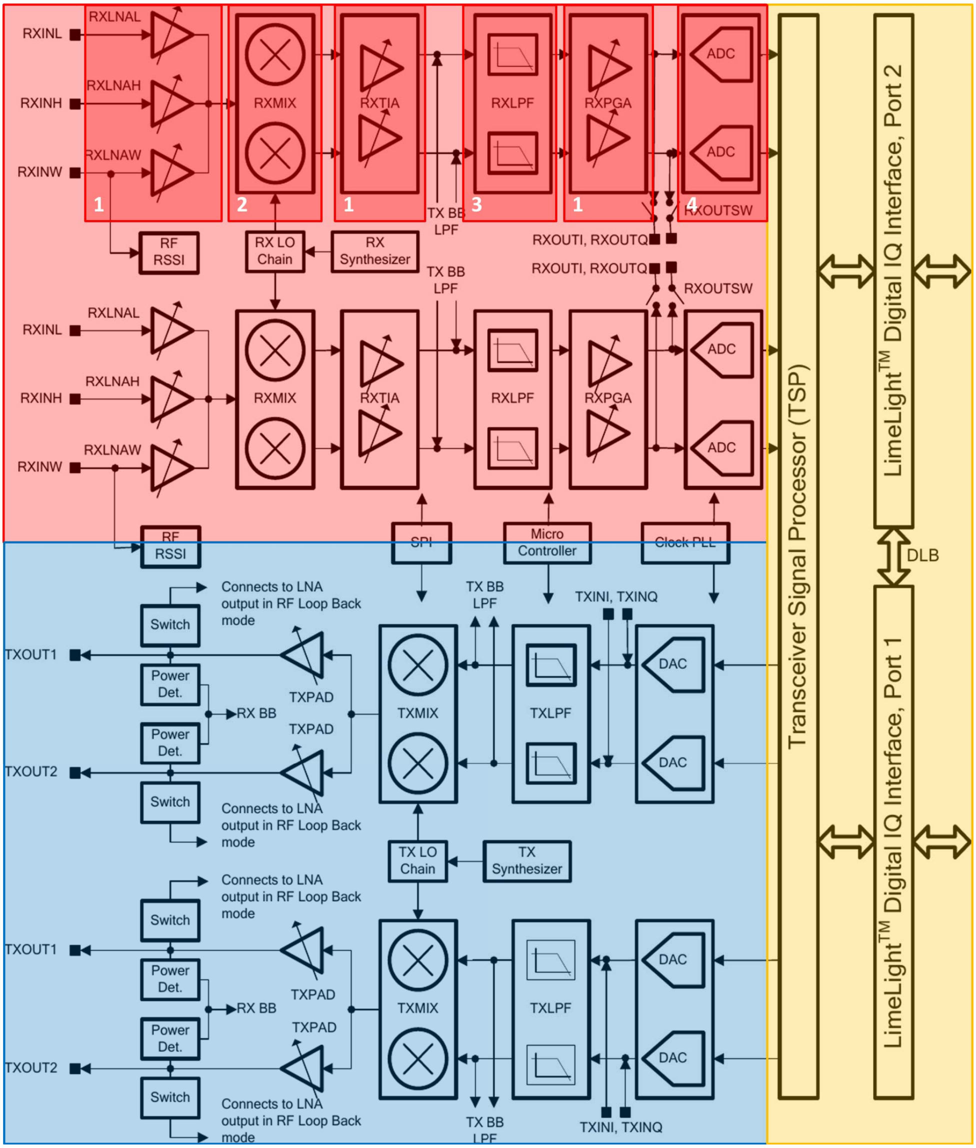

Figure 4.15: LMS7002M (adapted from datasheet [76]). The red highlight shows the redundant RX chain, including gains (1), mixers (2), filters (3) and ADCs (4). The blue highlight shows the redundant TX chain (which is not used for MarconISSta). The orange highlight shows the digital interface.

4.4.3 Objectives & experiment scientific requirements

The objectives were derived from the mission concepts (section 4.3) and the available hardware as follows. The primary objectives are:

- Analysis of spectrum use in VHF in the range 145.8–146 MHz
- Analysis of spectrum use in UHF in the range 435–438 MHz
- Analysis of spectrum use in L Band in the range 1260–1270 MHz
- Analysis of spectrum use in S Band in the range 2400–2450 MHz
- Detection of interferers using algorithms based on received signal strength, attitude information, frequency Doppler shift information and antenna gain pattern

The secondary objectives are:

- Analysis of spectrum use in VHF in the ranges 150.05–174 MHz
- Analysis of spectrum use in UHF in the ranges 400.15–420 MHz
- Analysis of spectrum use in S Band in the range 2025–2120 MHz
- Assessment of ARISS antenna radiation pattern

The frequency bands listed under primary objectives are the bands for which the available ARISS antennas are tuned. The concept for detection of interferers is explained in section 4.3.4. The bands listed under secondary objectives are of interest, as they are dedicated bands for satellite communication, however the antennas can only measure spectrum use within these bands if mismatch losses are accepted.

Based on the initial mission idea and hardware concept, experiment scientific requirements were drafted. These are required for each ESA project, since the mission planners schedule experiment time and assess feasibility studies based on the Experiment Scientific Requirements (ESR) document [72]. The main ESR requirements for MarconISSta are summarized in table 4.1. ESR requirements were frequently altered during early project phases, since the constraints of both the payload and the available ISS infrastructure were not fully defined during early stages of the project.

ID	Description
ESR-001	All hardware shall be COTS items.
ESR-002	The amateur radio antennas shall be used for reception of experiment data.
ESR-003	MarconISSta shall be powered via a USB power source.
ESR-004	The data shall be downlinked via the Joint Station LAN.
ESR-005	The config files and software updates shall be uplinked via the Joint Station LAN.
ESR-006	The hardware shall fulfill three functions: payload operation, payload data handling and standby mode.
ESR-007	MarconISSta shall have 1 GB storage capacity.
ESR-008	MarconISSta shall downlink up to 100 MB per day.

Table 4.1: Excerpt of the MarconISSta experiment requirements [72]

Shortly after the general hardware concept and experiment requirements were fixed, a Preliminary Interface Requirement Document (PIRN) was established [79] by ISS integration authorities. Besides general information, the PIRN contains a verification control matrix with technical requirements and the according verification procedures which are summarized in table 4.2. This matrix is later included in the Columbus Pressurized Payloads Interface Requirements Document [80].

Requirements	Verification Method
Structural, Mechanical, Environment & Stowage Interface Req.s	
Crew Induced Loads	A
Depressurization/ Repressurization Rates	A, RoD
On-Orbit Environment	A
On-Orbit Vibration Random Qualification Test	T
Shocks	A
Electromagnetic Compatibility	
Radiated Emissions	T
Radiated Susceptibility	T
DC Magnetic Field	A
Thermal Control Interface Req.s	
Total Heat Load	A
Sensible Heat Leak	A
Condensation Prevention	A, I

Requirements	**Verification Method**
Environment Interface Req.s	
Ionizing Radiation Dose	A
Single Event Effect (SSE), Ionizing Radiation	A
Materials, Parts & Processes Interface Req.s	
Materials and Parts Use and Selection	A
Commercial Parts	A
Exposed and Accessible Surfaces	I
Cleanroom Hardware	I
Metabolic Generation	A
Hazardous Substances	RoD
Fungus Resistant Material	RoD
Exposed Materials Offgassing, Toxicity	A
Human Factors Interface Req.s	
Identification Labeling	I
Sharp Edges And Corners Protection	I
Holes	RoD
Latches	RoD
Screws And Bolts	I,RoD
Burrs	I,RoD

Table 4.2: Excerpt of the Verification Control Matrix. The verification methods are **A**nalysis, **I**nspection, **T**est & **R**eview **o**f **D**esign.

These requirements were taken into account in the design phase of MarconISSta. Many design solutions are based on the Flight Safety Data Package (FSDP) of the Astro Pi, which is an external payload similar to the LimeSDR from a verification perspective [81]. The design steps for MarconISSta are summarized in the following section.

4.4.4 Development process

The simplified block diagram for MarconISSta was explained in figure 4.13. To satisfy all safety requirements and the needs of ARISS, more elements had to be implemented as depicted in figure 4.16.

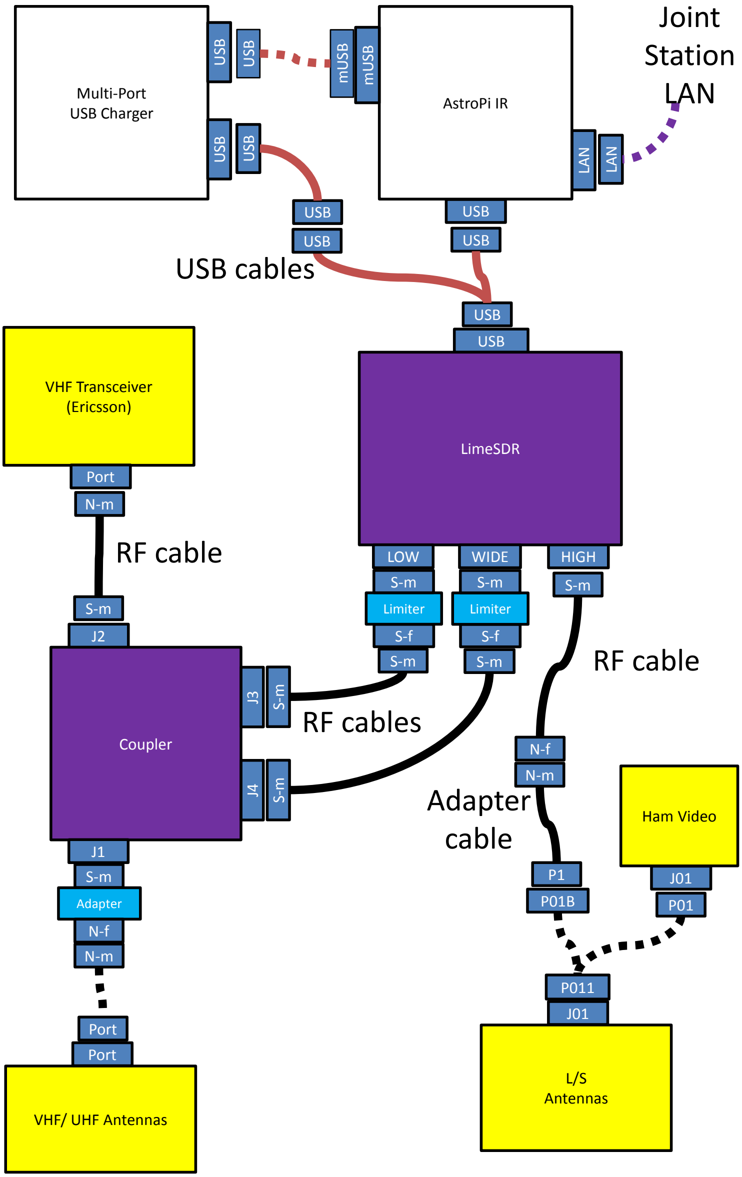

Figure 4.16: Detailed experiment setup. Purple components and cables with solid lines have been uploaded for MarconISSta (also see Annex A). All other components were already on board: White components belong to ESA, yellow components belong to ARISS.

The VHF/UHF antennas are currently used by ARISS for various amateur radio applications. The first design idea was to implement manual switches which allow to choose whether MarconISSta or the amateur radio device (an Ericsson M-PA VHF transceiver) is connected. This implementation has two major disadvantages. First, it requires crew time to operate the switch. Although switching only takes few seconds, a minimum of five minutes crew time has to be allocated to this action, which is costly and would constrain experiment runs to only few repetitions. Secondly, while the switch is set to connect MarconISSta to the antenna, the VHF transceiver is effectively not connected (open circuit). If the VHF transceiver would be accidentally operated during this state, the RF power would be reflected and potentially destroy the RF input of the transceiver. This also impedes the utilization of automatic switches.

To circumvent the need of a switch, ARISS member Lou McFadin proposed to use an RF coupler as shown in figure 4.16. The antennas and transceiver are connected to the main line of the coupler (J1 & J2), which results in a negligible loss of 0.25 dB [82]. The LimeSDR can be connected to both of the coupled ports (J4 & J3). The coupled forward port (J4) is the better choice to receive signals from the input (J1), while the coupled reverse port is more suitable to receive signals from the output (J2). Both ports introduce an additional loss of approximately 20 dB in the intended direction (J1-J4 & J2-J3) and an additional loss of 25-30 dB in the unintended direction (J1-J3 & J2-J4). This loss obviously decreases the relevance of the VHF and UHF bands significantly, however it was identified to be the only way to satisfy all safety concerns. Additionally, with no crew time needed, continuous operation of MarconISSta over the whole mission time is possible. Since two of the LimeSDR's RF connectors are available (*LOW* and *WIDE*), both coupled ports are connected.

To prevent damage to the LimeSDR inputs, RF limiters are included [83]. The current VHF transceiver transmits up to 5 W RF power. Including the coupler loss, this would result in up to 50 mW (17 dBm) at the LimeSDR input, which would damage the input circuitry. A new ARISS transceiver that is planned to be uploaded in 2019 can transmit even higher power. The RF limiters reduce any power that is higher than 30 dBm to 11.5 dBm, which is sufficient to protect the LimeSDR inputs. Including the coupler loss, the transceivers could transmit powers of up to 50 dBm (100 W) without harming the LimeSDR.

The LimeSDR's third input (*HIGH*) is connected to an ARISS L/S band antenna. There are two identical L/S band patch antennas outboard the Columbus module of which one is used by a ham video system (for video transmission to ground). The other patch antenna was not used and therefore available for MarconISSta. Both antennas share the same socket inside the Columbus module to which a Y–cable with proprietary connectors is connected. The proprietary connector has been an issue of concern for ARISS and they therefore demanded TU Berlin to upload an adapter cable that allows connection of typical N-type cables to the antennas. Therefore the adapter cable had to be manufactured and was uploaded along with a cable that connects the N-type cable to the LimeSDR SMA input. This matter explains why three cables are shown in figure 4.16 between L/S antenna and LimeSDR.

During the identification phase of potential SBC to control the LimeSDR, a feasible solution was found in a RaspberryPi computer. This system is one of the first COTS SBC that entered a mass market. It offers multiple USB ports, a LAN port, multiple input output capabilities and a full Operating System (OS). OS and data are stored on a micro SD card. During early negotiations with ESA and ARISS it was yielded that there already are two Raspberry Pi's aboard the ISS. These have been uploaded for ESA astronaut Tim Peake's mission *Principia* in 2015–2016. The Astro Pis have been optimized for use on the ISS and went through a very similar verification and safety process as MarconISSta. A valuable side effect is that the documentation for Astro Pi became available for MarconISSta, which helped during the assessment of mandatory and recommended design steps. Although the systems are using the first generation of RaspberryPi and there are newer and faster generations available, it was decided to use one of the Astro Pis to reduce the complexity of the project development and design workload. Sending a new RaspberryPi computer would have required lengthy safety and security processes, since each computer that is connected to the ISS network is reviewed with special caution. Additionally, hardware and verification cost would at least have doubled the cost of the project.

The Astro Pi is powered by a COTS multi-port USB charger. Although it provides enough power (up to 60 W), a long cable (4.5 m) has led to under-voltage conditions in the past. Since the LimeSDR requires considerably high power, an additional USB power source is needed. Therefore, the LimeSDR is connected to the Astro Pi through a USB Y-cable. The third port of the cable is connected to the USB charger (through an extension cable) to prevent under-voltage. The Astro Pi's LAN port is used to connect MarconISSta to the JSL network, through which commands and experiment data are forwarded from/ to the Ku band antennas for uplink and downlink.

Figure 4.17: Astro Pi [81]. The custom housing includes buttons, an LED matrix and additional holes for sensors. The bottom lid is supplemented with a grid structure to increase heat dissipation.

Figure 4.17 shows the Astro Pi from different perspectives. Since it is an educational experiment, it has several buttons for manual interaction, an LED matrix and various sensors, including a camera. These peripherals are not used for MarconISSta. The bottom lid uses a grid structure to increase the surface of the housing which improves heat dissipation. To prevent injuries, all edges have been rounded and projecting parts avoided. These design considerations have been adopted for the LimeSDR housing.

Figure 4.18 presents the CAD model which was completely designed by students (see Annex B for more details). The housing consists of two lids. The LimeSDR is fixed to the bottom lid, which will later be fixed to a ground plate using Velcro. The top lid and bottom lid are connected with four screws. The bottom lid incorporates two heat pipes (not displayed in the figure) that improve heat dissipation from the FPGA and the RF receiver chip. To further distribute the heat, a grid structure similar to the Astro Pi's has been implemented on the top lid. All edges have been rounded off to prevent harm to astronauts. The surface of the aluminum housing is anodized to protect the system from its surrounding (and vice-versa).

Figure 4.19 shows the bottom lid and LimeSDR. Gap fillers are later attached to the transceiver chip (center left on the board) and FPGA (center component of the board) to improve heat dissipation. Three of the RF u.FL connectors are used for the *LOW*, *WIDE* and *HIGH* input ports. SMA connectors are fixed to the housing, since these connectors offer higher stability during installation than u.FL connectors. Figure 4.20 depicts the finished housing. Laser engravings show the project logo, additional laser engravings are added to each port.

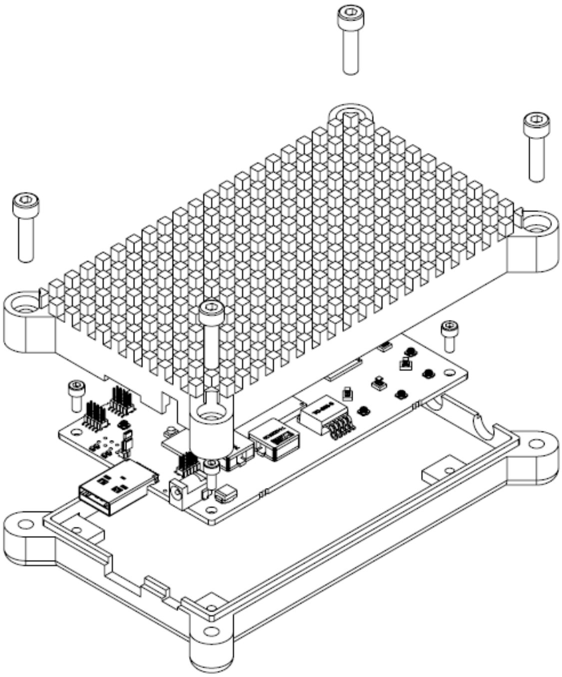

Figure 4.18: MarconISSta CAD model [74]. Four screws fix the LimeSDR to the bottom lid. Four screws and integrated helicoils fix top and bottom lid to each other. The housing incorporates ports for three RF inputs, a USB connector and a DC input.

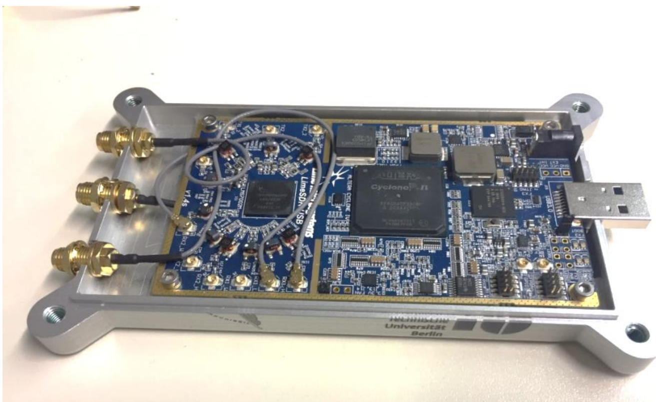

Figure 4.19: Bottom lid of housing and LimeSDR [84]

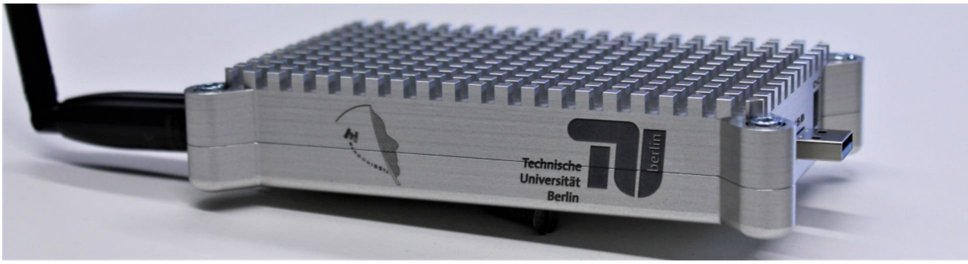

Figure 4.20: LimeSDR payload in its housing [74]. The housing is anodized, sharp edges are rounded off to prevent harm to astronauts.

4.4.5 Verification

The verification matrix (see table 4.2) includes most verification steps that are requested by the Columbus integration authorities. Some additional requirements are set by ESA's safety review panel. The main goal of the ESA safety review is to finalize a hazard report that contains all potential hazards of a payload. The Flight Safety Data Package (FSDP, [84]) contains supporting information on hazards and shows the development status during each safety review. Many of the hazards that need to be assessed for safety overlap with the verification requirements by the Columbus integration authorities.

The safety review process is divided into three phases. For each phase, an FSDP is prepared with the goal to close all hazards with the third and final review. It would exceed the scope of this work to discuss the full safety analysis and documentation, however the main verification steps are summarized in this chapter. The most relevant and applicable NASA, ESA & ISS documents for the design and verification process are summarized in table 4.3 to provide an overview of helpful documentation for this process.

Author	Doc. No.	Description	Source
Airbus Group	COL-RIBRE-SPE-0164	COLUMBUS Pressurized payloads interface requirements document	[80]
Airbus Group	COL-RIBRE-MA-0007	COLUMBUS Payloads Accommodation Handbook	[85]
Airbus Group	COL-RIBRE-PL-0144	COLUMBUS Pressurized payloads generic payload verification plan	[86]
NASA	SSP 30599	Safety Review Process	[87]

Author	**Doc. No.**	**Description**	**Source**
NASA	JSC-29353	Flammability Configuration Analysis for Spacecraft Applications	[88]
NASA	SSP 50835	ISS Pressurized Volume Hardware Common Interface Requirements Document	[89]
NASA	SSP 51700	Payload Safety Policy and Requirements for the International Space Station	[90]
NASA	SSP 57000	Pressurized Payloads Interface Requirements Document	[91]
NASA	SSP 50423	ISS Radio Frequency Coordination Manual	[92]
ESA	COL-ESA-RQ-014	COLUMBUS EMC & Power quality requirements	[93]
ESA	ESA-HRE-IPL-RQ-0002	Product Assurance and Safety Requirements for ISS Pressurized Payloads	[94]
US DoD	MIL-STD-461G	Requirements for the control of electromagnetic interference characteristics of subsystems and equipment	[95]
US DoD	MIL-STD-462D	Test method standard for measurement of electromagnetic interference characteristics	[96]

Table 4.3: Recommended and applicable documentation for the integration process of ISS payloads

Touch temperature test

Figure 4.21: Touch temperature test [84]

A major issue for internal ISS payloads is crew safety. Besides prevention of sharp edges and open circuits, the touch temperatures have to remain in a safe range. MarconISSta includes no active cooling elements such that the temperature cannot sink below room temperature. For this reason only maximum temperature tests had to be conducted. According to the applicable documents [94, 89], the maximum surface temperature of an experiment shall not exceed 45 °C at an ambient temperature of 35 °C. Out of all MarconISSta components only the LimeSDR was tested, as it is the only active component. Two temperature sensors were attached to the LimeSDR: One was fixed on the top side, inside the heat dissipated grid structure and above the location of the FPGA which is considered to be the hottest part. The other sensor was fixed on the front side of the housing for reference. The component was subsequently inserted in a thermal chamber

(Vötsch VT4002) as seen in figure 4.21. Cables for connection to a computer and for the temperature sensors were led outside the chamber. After a temperature of 35 °C was reached, the LimeSDR was powered and switched into experiment mode. The temperature on both sensors did not rise above 40.7 °C. Additional measurements at room temperature (22 °C) yielded temperatures not higher than 26.2 °C. These temperatures are sufficient to pass touch temperature testing.

Vibration testing

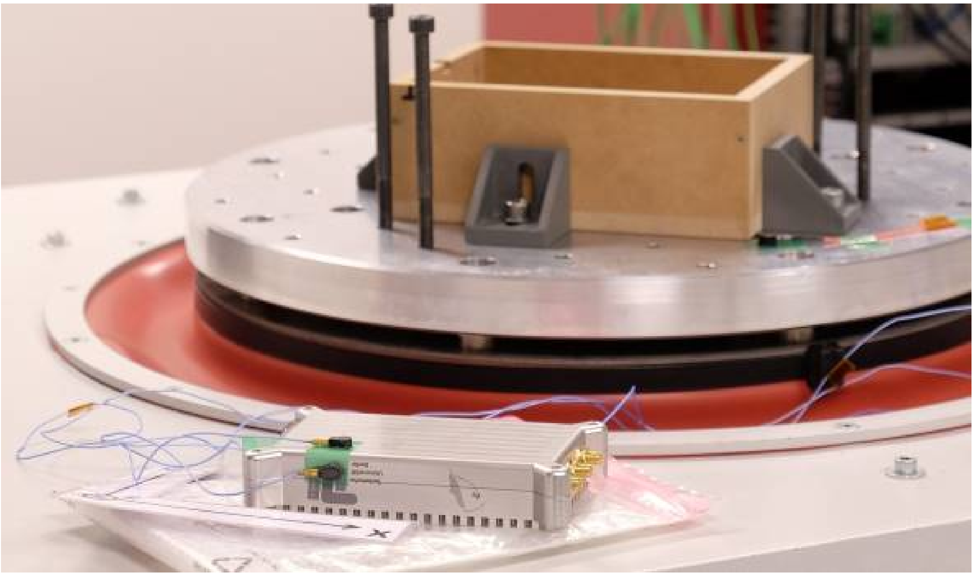

Figure 4.22: Vibration testing [97]. Accelerometers were placed on different surfaces to test vibration responses in three axes.

Vibration testing was conducted to guarantee that the system will not be damaged during launch. All components of MarconISSta are launched inside a Cargo Transfer Bag (CTB). These bags are soft, foamed boxes. Furthermore, the components are placed in bubble wrap bags for additional dampening of vibrations and shocks. As defined in [89], specific test levels apply for soft-stowed components. The biggest challenge during vibration testing was to find a flight-like configuration of the device under test. Again, only the LimeSDR was tested, as the other components (RF coupler, cables, adapters) are not significantly affected by vibrations or shock. The applicable procedures do not state in which way the device under test shall be fixed to the vibration table. Since the items are soft-stowed, fixing the item on the table would not represent flight-like conditions. For flight-like conditions a CTB would be needed. As the CTBs usually carry various experiments, these other experiments would have been needed for the most realistic test case. After negotiations with the launch authorities it was agreed to build a small wooden box, in which the LimeSDR inside a bubble wrap bag was placed (figure 4.22). Acceleration sensors were attached to test response to vibration in three axes. As expected, the LimeSDR was not influenced by vibration testing. No damage occured and screws and connectors remained tightened.

EMC testing

EMC testing was conducted in accordance with both ESA EMC requirements [93] and applicable MIL standards [95, 96]. Since MarconISSta is not directly connected to any safety-relevant systems, only radiation tests were required, while conduction tests were considered as obsolete. Therefore, tests included radiated emissions and susceptibility for both magnetic and electrical fields. All RF parts (excluding cables that are part of the Columbus setup) have been integrated in the test setup, as figure 4.23 shows. The computer to drive the LimeSDR has been placed outside the EMC test chamber. All tests did not show anomalies and no test thresholds were exceeded.

Other verification steps

Other verification steps were conducted by analysis, inspection and review of design. Many safety aspects could be closed because of the small dimensions and mass of the experiment. For example, offgassing analysis is only required for systems with non-metallic mass greater than 20 lb (9.072 kg) [94]. (Non-ionizing) Electromagnetic radiation is only considered as a hazard if RF power of more than 10 mW is emitted. The system was designed to be as simple as possible, excluding moving parts, shatterable material and batteries. Potentially flammable components were wrapped in fibre-glass tape in accordance with [88]. In summary, all issues on potential hazards were closed and the hazard report was finalized and agreed with ISS safety officers by February 2018.

Figure 4.23: Setup for EMC testing [98]

4.4.6 Software & operations

Parameter	**Values**
Antenna select	LOW, WIDE, HIGH
Frequency range	100 kHz to 3.8 GHz
Sample rate	typically 1–15 MHz
Time interval	continuous or fixed time
FFT bins	No. of bins for spectrum analysis
Gains	Gain setting for LNA, PGA and TIA
Windowing	Optional choices for different window functions

Table 4.4: Configurable parameters for *Soapy Power* software

For software implementation, the same approach was taken as for the hardware development. All elements were designed with the goal to minimize crew time and ground control interaction. In order to prevent software failures, existing and flight-proven software was used where possible. ESA provided a security hardened Raspbian OS which simplified the software security processes significantly. The security hardened Raspbian differs from a normal Raspbian OS in the way that no external access to the system is possible, except for selected secure ports for ground control. Apart from this, the OS works like a normal Raspbian system. To operate the LimeSDR, driver packages and support libraries are installed. The open-source software *Soapy Power* [99] is used for spectrum analysis. This software is command-line based and does not require a graphical interface. Various parameters can be specified as summarized in table 4.4.

Since it would be to costly to ask ISS crew to execute each single run of the program and ground control only accesses the AstroPi approximately once a week, an automatic routine was implemented as can be seen in figure 4.24. Code snippets which were developed by the student team can be found in Annex C. The payload operator plans in advance which frequency bands should be investigated during which times. For each experiment run, the times and parameters in accordance with table 4.4 are defined in a "timing file". Ground control up-links this file to the ISS on a weekly basis. A service is installed on the Raspbian OS that continuously checks whether a new timing file (and with that new experiment runs) has been uplinked. In this case, the experiment runs are executed at the times defined in the file. The measurement data is stored in a defined folder in form of Comma Separated Values (CSV) files. This file contains one line per

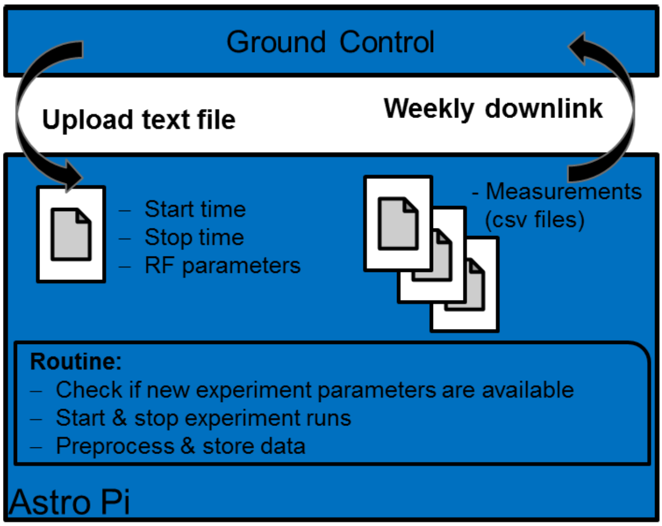

Figure 4.24: Operations scheme [97]. The whole routine can be conducted without crew interaction.

measurement, consisting of the duration of the measurement, the start and stop frequency, the bandwidth resolution and the measurements. If a frequency range of 5 MHz and 512 bins were selected, each line will contain 512 measurements with a bandwidth resolution of 9.77 kHz. A week of continuous operation will create approximately 800 MB of data. Before downlink the data is compressed and down-sized to approximately 100 MB. The data is downlinked during the weekly commanding windows and forwarded to TU Berlin. The whole procedure does not require crew interaction after the system has been set up.

While quick analysis of data can be done using MATLAB/ Octave, students developed a tool chain for more detailed data analysis. After reception the CSV data is stored in an SQL database. Each time-stamp is linked to the current position of the ISS, based on TLE information. Additionally, comments can be added to each measurement and stored in the database. A user interface was implemented via which the user can select the frequency band of interest, a time interval and the region of interest. For the chosen intervals, either a heat map and/ or a waterfall diagram can be visualized. Data can be filtered to remove constant noise and the color map of visualization can be adapted. The current track of the ISS is provided to simplify identification of signals. Figure 4.25 shows the implemented user interface, figure 4.26 shows the waterfall tool. Examples of heat maps will be shown in the following section.

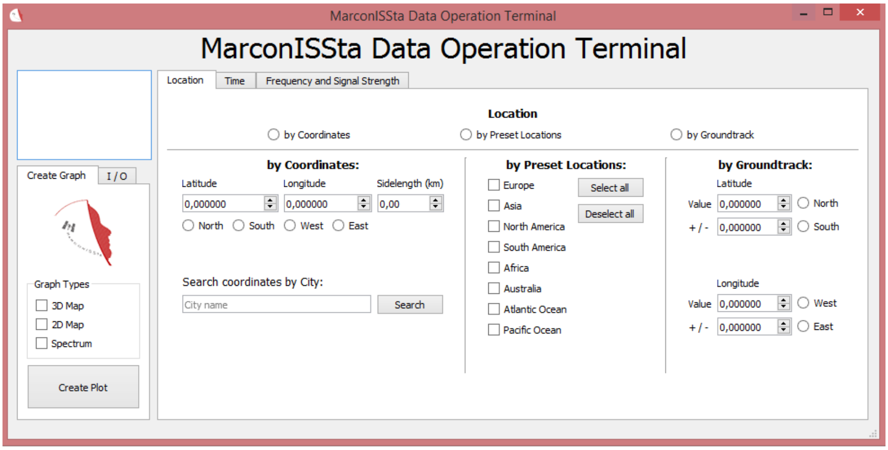

Figure 4.25: MarconISSta user interface. Front-end and back-end were developed by a group of five students.

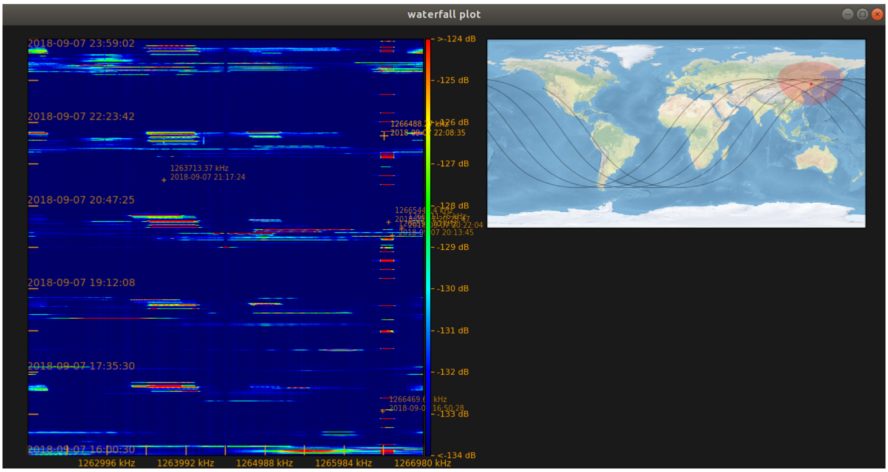

Figure 4.26: MarconISSta waterfall visualization tool, developed by a student. Hovering the mouse over the signal will automatically show the position of the ISS at the time of recording.

4.4.7 Early flight results

MarconISSta was launched to the ISS aboard a Cygnus spacecraft on May 21st 2018. The system was subsequently stowed until crew time for installation could be allocated. ESA's Horizon mission, under which MarconISSta's launch was funded, started with the boarding of astronauts Alexander Gerst and Serena Auñón-Chancellor as well as cosmonaut Sergej Prokopev on June 8th 2018. On August 13th 2018 NASA astronaut Serena Auñón-Chancellor installed MarconISSta on a desktop plate inside the Columbus module using a step-by-step instruction that was developed by TU Berlin and BioTESC. The flight setup can be seen in figure 4.27.

This section only contains preliminary flight results, as analysis and interpretation of data will require several months. Up-to-date flight results and other MarconISSta activities are regularly published on the project webpage [100]. Rather than providing results on the assessment of spectrum use and capacity for future systems, this section shall demonstrate the capabilities of MarconISSta. Therefore, exemplary heat maps for VHF, UHF, L band and S band are presented. Each measurement run is either one or two hours long and about 3.5 MB to 7 MB in data size. Since the Astro Pi is based on a comparatively slow Raspberry Pi 1 Model B+, the sample rate was usually set to 5 MHz and never higher than 12 MHz. The number of FFT bins was usually set to 512 bins and not higher than 1024 bins. Sample rate and number of bins influence the time resolution. The higher the sample rate and number of bins, the longer is the computational time to record and store a measurement. For 5 MHz and 512 bins, each measurement takes three to four second, while for 10 MHz and 1024 bins each measurement takes approximately 10 seconds [97].

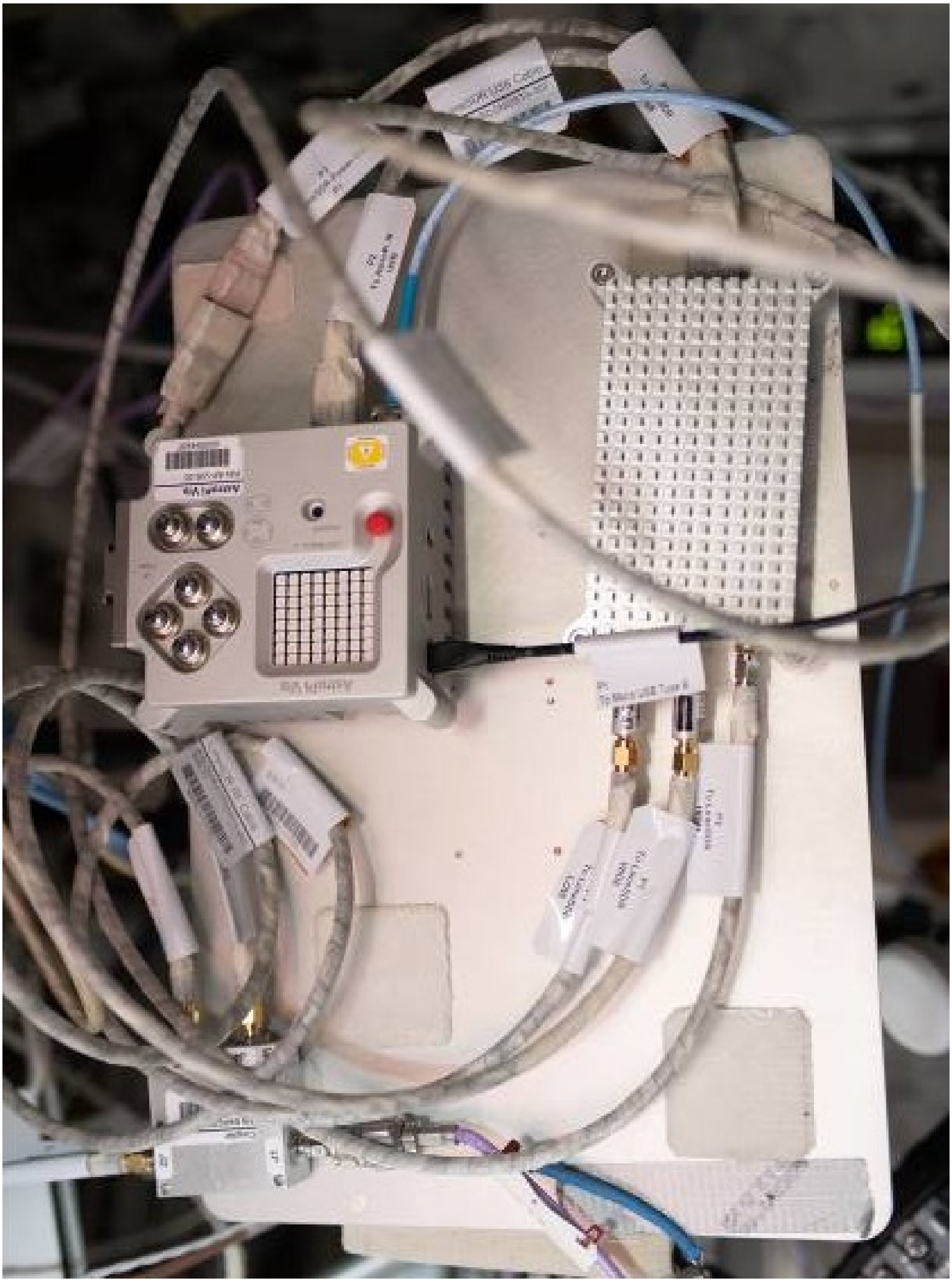

Figure 4.27: MarconISSta on the ISS: Astro Pi (top left), LimeSDR (top right), RF coupler (bottom left) and various cables were installed on August 13th 2018.

VHF spectrum assessment

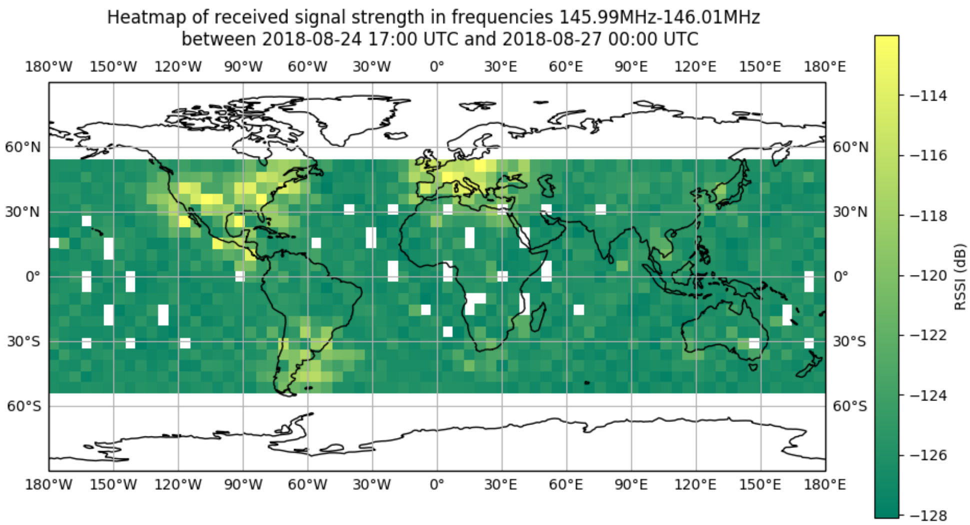

Figure 4.28: Heat map of frequency use on 146 MHz. White spots represent regions where no measurements where obtained. Green color indicates low signal strength, while yellow color indicates high signal strength.

Figure 4.28 shows a heat map of the spectrum use in VHF bands, focusing on frequency 146 MHz. Green color indicates low RSSI levels, while yellow color indicates high RSSI levels. At the time of writing, no calibration of the dB level has been conducted. As for most spectrum analysis systems, the *Soapy Power* output is "dBFS" (dB Full Scale). Although the LimeSDR has internal calibration procedures to normalize the input signal strength, it was decided not to publish absolute power levels, e.g. dBW or dBmW. An additional reason for this is the fact that losses of the existing ARISS cables and the antenna performance are only vaguely known. When more measurement data becomes available, more meaningful statements on the absolute power levels can be made. It is planned to transmit defined RF signals from various ground stations in order to assess the antenna radiation pattern and to verify the absolute received signal strength. Up to this point, the heat maps visualize only relative dB values.

The spatial resolution of the map is 5° in longitude and latitude. In other words, all measurements which were received on the observed frequency in a spatial box of 5° longitude and latitude are averaged for the visualization. This spatial resolution allows to produce full heat maps of the investigated frequency channel after approximately three days. If during these three days temporarily no data is available, this can result in gaps in the heat map, as visualized by white blocks in figure 4.28 (e.g. pacific region and Africa). Including more data will fill these gaps. As more data becomes available, the grid size can be decreased to produce a higher level of detail.

The heat map for 146 MHz shows a high use of the frequency in North America, southern regions of South America and Europe. Lower use can be seen in South Africa, eastern Asian regions and partly in Australia. The reasons for this distribution are various. First, regions with larger populations use more RF devices and consequently the human-made noise is high. The reason why VHF has a larger occupation of bandwidth in North America and Europe is that more amateur radio operators originate from these regions compared to other densely populated regions like India or China. For the latter-mentioned regions, other frequency channels are more frequently used.

A deeper analysis of the origin of use in other regions, e.g. in South-East Asia, will be undertaken in the future. Second, the use of ARISS systems aboard the ISS is a strongly influencing source. In VHF and UHF, signals that are sent from the ARISS transceivers will be led into the RF inputs of the LimeSDR via the integrated coupler. The VHF transceiver on the Columbus module is mainly used for school contacts and for Automatic Packet Reporting System (APRS). In APRS mode, messages that are received by the ISS are digipeated [101]. Additionally, a beacon with a two-minute cycle is often active. The transceiver signals which are transmitted with 5 W output power enter the LimeSDR with up to 12 dBm (upper output limit of the RF limiters). Obviously, these signals highly influence the heat maps. Figure 4.29 compares the use of two different VHF frequencies (145.8 MHz and 145.9 MHz) during the same time-span. For most regions, the usage is similar, except for a higher use of 145.8 MHz in the Pacific region around Hawaii. Further investigation is needed to identify the source for this unequal use.

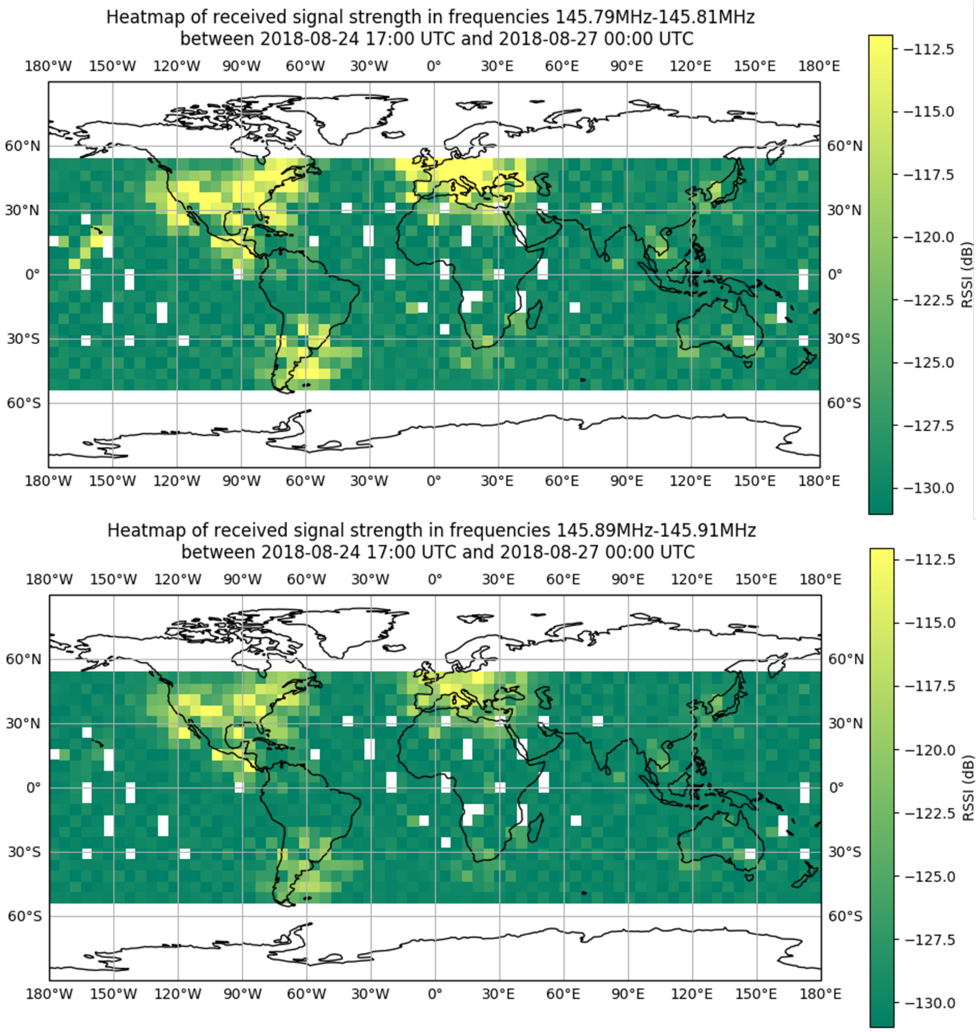

Figure 4.29: Comparison of spectrum use on 145.8 MHz and 145.9 MHz during the same time-span. Only minor deviations can be seen on the preliminary results for VHF channels.

UHF spectrum assessment

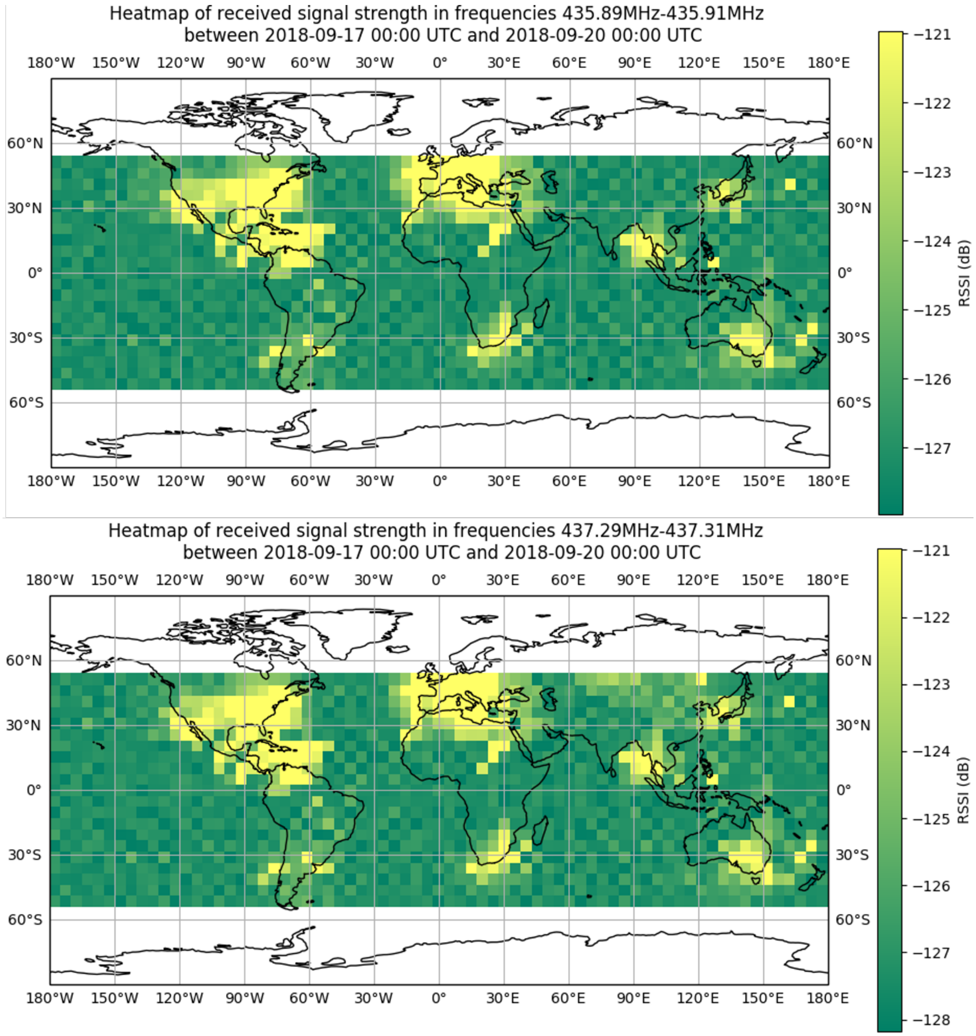

Figure 4.30: Comparison of spectrum use on 435.9 MHz and 437.3 MHz during the same time-span. Deviations can be seen in the Russian and Eastern Asian region.

Figure 4.30 shows the use of the UHF band for two frequencies (435.9 MHz and 437.3 MHz). The UHF scenario looks similar to the VHF scenario. The highest use is observed in North America and Europe. There seems to be a higher use of

UHF in South Africa. Additionally, higher use is observed in the Bay of Bengal area. Another preeminent deviation from the VHF results is that a difference can be seen in the usage of the two observed frequency. While the use is similar most over the world, the frequency 437.3 MHz seems to be more heavily used over the Russian and Eastern Asian region, while 435.9 MHz is not used in this region. As well as for VHF, more detailed maps and longer observations will improve this analysis.

L band spectrum assessment

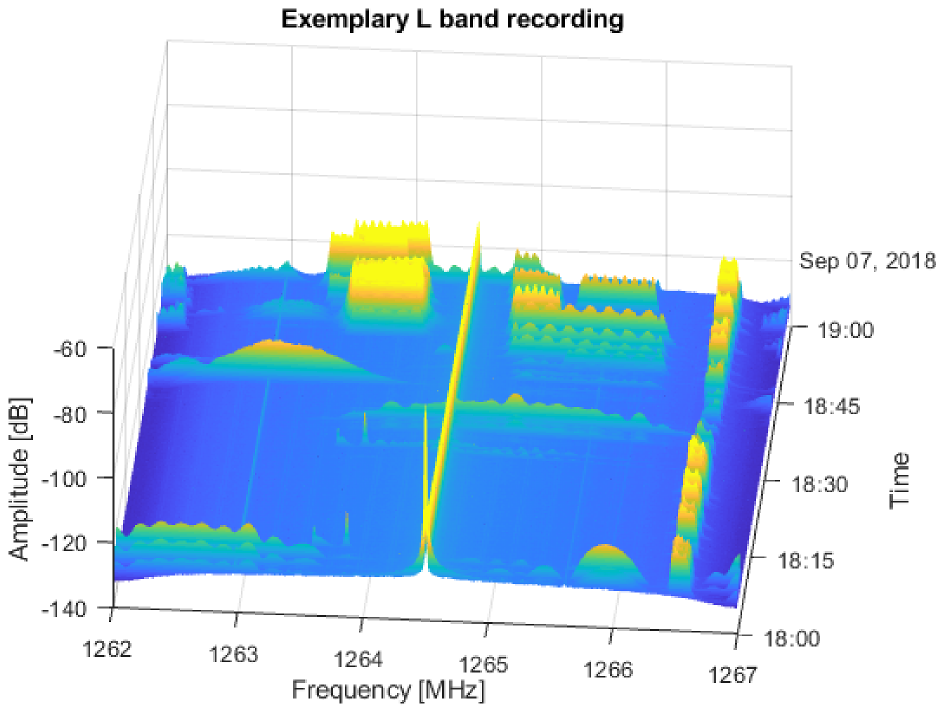

Figure 4.31: Visualization of a 1-hour measurement in L band

The L band amateur-satellite frequencies turned out to be of particular interest, since it is frequently used world-wide. Figure 4.31 shows this for an exemplary 1-hour measurement. In this visualization, the signal strength over the defined frequency range (1262–1267 MHz) and time (one hour) is shown. High signal levels can be seen with different shapes and duration. A major part of the MarconISSta data analysis will deal with the identification of signal shapes and origins.

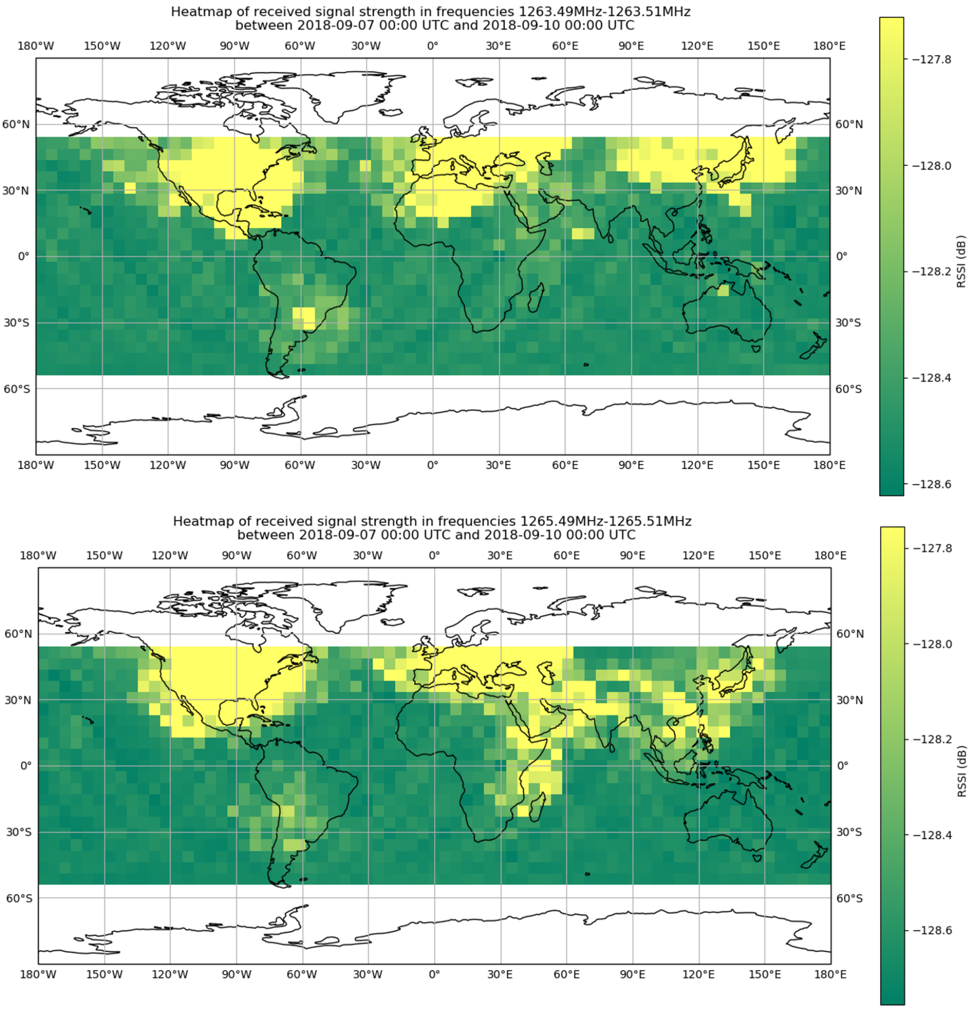

Figure 4.32: Comparison of spectrum use on 1263.5 MHz and 1265.5 MHz during the same time-span. Deviations can be particularly seen in East Africa, but also in the Eastern Asian region and in South America.

Additionally, varying use on different frequencies can be seen. Figure 4.32 emphasizes this finding. As for the other bands, all L band channels are used to capacity in North America and Europe. Many signals can be found in Asia, too. For other regions, the use of two exemplary frequencies shown in the figure differs. While frequency 1263.5 MHz appears not to be used in the East African region, frequency 1265.5 MHz is highly used. In South America, 1263.5 MHz seems to be used in the border region of Argentina and Uruguay, while 1265.5 MHz is used in the border region of Chile, Bolivia and Peru.

S band spectrum assessment

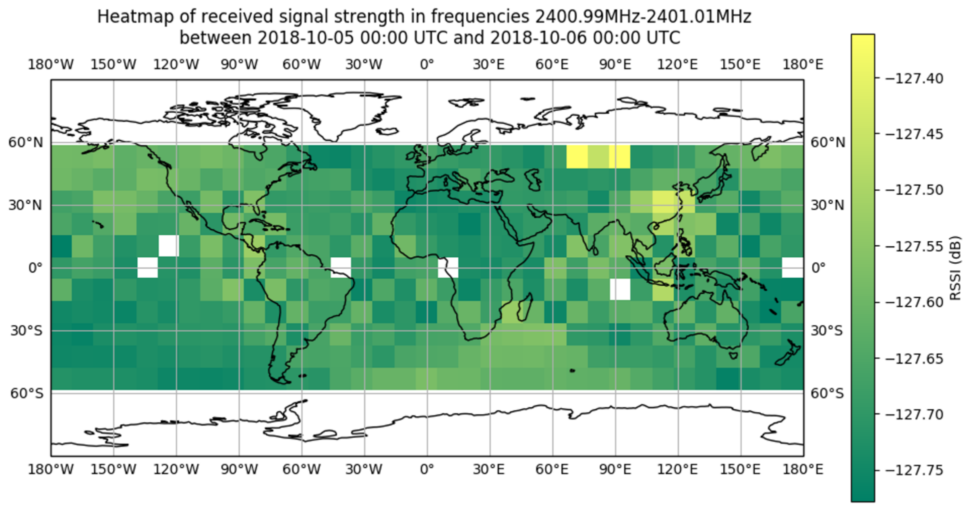

Figure 4.33: Spectrum use on frequency 2401 MHz. The grid resolution was set to 10 degrees (longitude and lattitude).

As the S band amateur-satellite frequency range is the widest of all bands under investigation, more measurement time is needed to complete the investigation. Only low-detail heat maps can be plotted after preliminary analysis. The first result of the investigation is that the S band is not as highly used as the other bands. Figure 4.33 shows a heat map for 2401 MHz. The resolution was set to 10 degrees per grid in longitude and latitude. The whole range from 2400 MHz to 2450 MHz will be investigated in the future.

4.4.8 Conclusion of MarconISSta experiment

MarconISSta was developed and delivered for upload to the ISS in less than 15 months. The system is operational on the Columbus module from August 2018 until February 2019, generating approximately 800 MB of spectrum analysis data per week. VHF, UHF, L and S band are being investigated. First results yield that the experiment has been a huge success, based on the quality of the data and the feedback from research groups, radio amateurs and regulatory authorities world-wide. Significantly more time is needed to finalize data analysis and to draw conclusions of the identified use.

Future applications for the MarconISSta hardware are currently discussed between TU Berlin, ESA and ARISS. After the original experiment time ends in February 2019, the hardware will be handed over to ARISS. The LimeSDR will fit well into planned ARISS experiments, including new transceiver systems, new amateur-radio applications and potentially ARISS-owned Astro Pi successors. SDR experiments, for example experimental software radio blocks, are planned as well. TU Berlin will put effort into the ongoing collaboration with interested parties to initiate new applications for the MarconISSta experiment hardware.

Despite the success of the experiment, there are some major drawbacks of MarconISSta. First, the investigation can only cover terrestrial regions that are under the foot print of the ISS. The highly used polar regions cannot be observed. Second, the ISS antennas are always pointing Nadir. It is suspected that most satellite signals cannot be recorded. Optimization of the localization algorithm (see chapter 4.3.4) cannot be done without changing the attitude of the receiving antennas. Third, the RF coupler in the VHF and UHF line introduces losses of 20–30 dB such that low power signals cannot be recorded. Global heat maps on the use of bands might be misinterpreted, if the coupler loss is not taken into account.

For these reasons, it is desirable to have a on-orbit spectrum analyzer that is independent from the ISS constraints. The LimeSDR payload has been found to fulfill all functional requirements for spectrum analysis. Therefore, a small satellite spectrum analysis payload based on LimeSDR has been developed that is introduced in the following section.

4.5 SALSA – Spectrum Analysis of LEO Satellite Allocations

The project SALSA was conducted between October 2016 and June 2018. Over this time-span a spectrum analyzer payload was to be developed and qualified for use in LEO. The payload was developed such that it can fit in any small satellite that provides enough space for a 10 cm by 10 cm PCB board. However, a favored satellite bus was already identified early in the process and accordingly an integration concept was prepared as part of the SALSA project. This chapter will introduce the requirements of the payload and the development process. Furthermore, it will present the engineering qualification model as well as the qualification results and future satellite integration work. It should be noted that only the project management and system level tasks were conducted by the author. The detail design (PCB design, software implementation) and qualification campaign were conducted by a two-person team and various student theses. Therefore, only top-level aspects are summarized in the following subsections.

4.5.1 Requirements

MarconISSta successfully uses the LimeSDR for spectrum analysis. The device was installed as an internal Columbus module payload. When integrated into a satellite, obviously some of the requirements change. Table 4.5 summarizes some of the most relevant requirements for the payload design. SALSA is planned to be operational for at least one year, yielding that the payload has to withstand space environment for this time. Accordingly, the system had to be designed to endure vacuum, changing temperature conditions, radiation and mechanical stresses. The examined frequency ranges are similar to the ones chosen for MarconISSta, excluding the L band, as the satellite bus that was planned to be used does not support L band and because at the time of setting the requirements it was not expected that the L band will be used frequently for small satellite operations. The bands mentioned in MR05 and MR06 refer to the bands that are being investigated under WRC-19 agenda item 1.7, relating the practical implementation of spectrum analysis to the regulatory investigations in the previous chapters. The payload shall have its own processing and storing units, allowing data handling independent from the satellite bus. Since most satellite systems use frequency channels of typically 10–25 kHz, a bandwidth resolution of 10 kHz is considered to be sufficient for heat map generation. If the payload is used for localization, the bandwidth resolution shall be lowered to 1 kHz to improve the resolution needed for Doppler shift investigation.

ID	Description
MR-01	The payload shall withstand mission lifetimes of at least one year.
MR-02	The payload shall be qualified for operation in LEO.
MR-04	The payload shall be designed to measure frequencies in the range 145.80–146.00 MHz.
MR-05	The payload shall be designed to measure frequencies in the range 150.05–174.00 MHz.
MR-06	The payload shall be designed to measure frequencies in the range 400.15–420.00 MHz.
MR-07	The payload shall be designed to measure frequencies in the range 435.00–438.00 MHz.
MR-08	The payload shall be designed to measure frequencies in the range 2025.00–2290.00 MHz.
MR-09	The system shall be able to monitor frequency ranges of at least 3 MHz bandwidth.
FR-01	The payload shall include an RF receiver, a processing unit and a storage device.
FR-05	The payload shall be designed to fit into a 1U CubeSat.
FR-08	In lower band (VHF, UHF) global assessment analysis, the minimum bandwidth resolution shall be 10 kHz.
FR-10	In interference tracking mode, the bandwidth resolution shall be 1 kHz.

Table 4.5: Excerpt of the SALSA requirements

4.5.2 Design & development process

As mentioned before, the LimeSDR was taken as design baseline for the on-orbit spectrum analyzer. Lime Microsystems emphasize their endorsement of open source systems and therefore publish the PCB schematics and drawings for free use. This was the main reason why LimeSDR was chosen as baseline instead of other systems or completely new, self-developed designs. Another aspect is that the LimeSDR incorporates most components and functionality that are needed for a satellite payload. Figure 4.34 depicts the schematic overview of SALSA components and the required functional blocks. A controlling unit is needed to command all components, e.g. configure the payload, start and stop experiments or store and forward data. In the case of LimeSDR, this is mainly done by the computer that it is connected to. The LimeSDR incorporates a microcontroller, however it is mainly used to control signal flow via the USB interface. As USB is not a typical interface for satellite systems, it was decided to replace it by a more common SPI interface to the satellite bus. A microcontroller (STMicroelectronics STM32F4) was added for commanding and configuration, taking over the functionality of the Astro Pi computer in the case of MarconISSta. A watchdog constantly observes the correct functionality of the system and resets the controller in case of anomalies.

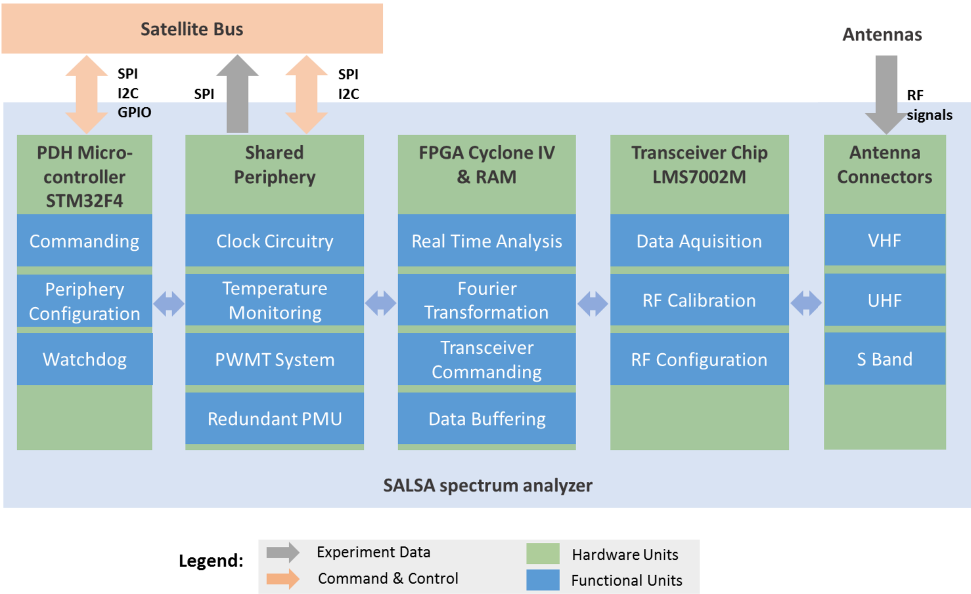

Figure 4.34: Schematic overview of SALSA (adapted from [102])

Most peripheral components were already existent on the LimeSDR design as well. The clock circuitry allows setting various clock frequencies according to the needs of all components. With that, the sampling rate of the transceiver can be adjusted independent from clock speeds of microcontroller and FPGA. Temperature monitoring is included close to the hottest devices (microcontroller and FPGA) to observe heat generation and distribution. Also, a PMU, consisting of two redundant 1 GBit flash memory units, is added to the design to store payload data. The FPGA (Altera Cyclone IV) and supporting RAM blocks were present in the LimeSDR design, too. While the FPGA is mainly used for waveform generation of TX signals in the case of LimeSDR, it shall be used for FFT generation in the SALSA payload. Additionally, transceiver commands are forwarded and payload data is buffered and pre-/ post-processed. The transceiver chip (Lime Microsystems LMS7002M) is the core component of the payload. Since TX capabilities are not needed for SALSA, TX analog circuits were removed from the design, while the six RX connectors were slightly adjusted to allow the addition of shielding of RF circuitry.

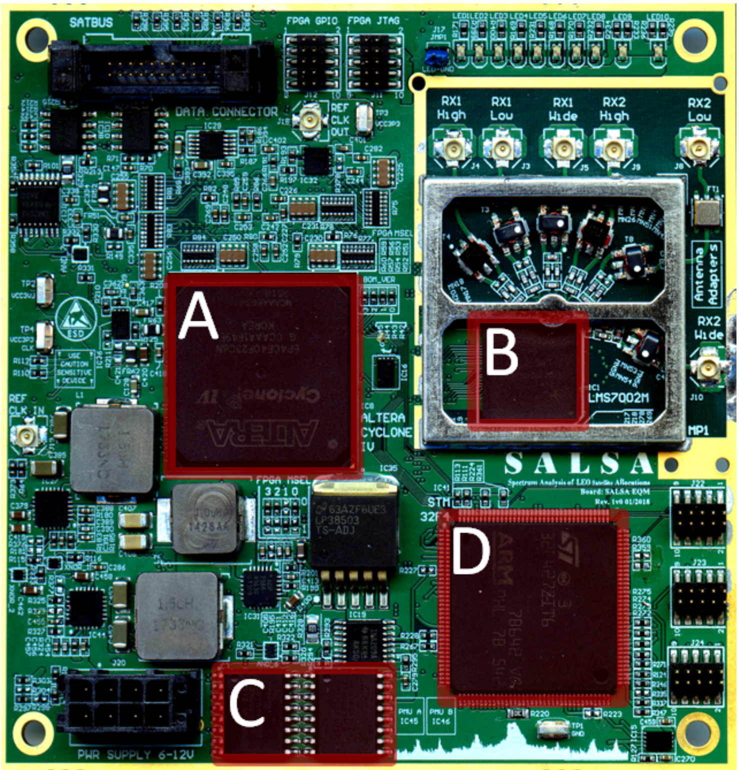

Figure 4.35: SALSA EQM, top view [103]. A: FPGA, B: Transceiver Chip, C: PMUs, D: Microcontroller. Annex D shows top and bottom view in more detail.

The hardware was implemented in a two-step approach. In a first iteration, a development model consisting of two boards was designed and tested. One board comprises the RF circuitry, FPGA and periphery. Its main difference to the LimeSDR is the change from the USB interface to SPI interface. The other board comprises the command and control unit (microcontroller). Once the functionality of both units was tested and verified, an engineering model in flight-like configuration was designed and manufactured. Figure 4.35 shows the hardware implementation of the SALSA EQM. The design has shown that the components of the SALSA payload need to be densely integrated. The payload is optimized for taking measurements in the range of 100 kHz to 2.5 GHz. The transceiver chip is reconfigurable such that gains, sample rate, decimation and other parameters can be modified. The FPGA calculates the FFT, typically with a bin size of 4096 bins and a sample rate of 10 MHz. The data is then stored in the PMU and can later be forwarded to the satellite bus and subsequently downlinked to the ground station. The power monitoring system (PWMT) makes sure that single event effects cannot harm the main components through high voltages or currents.

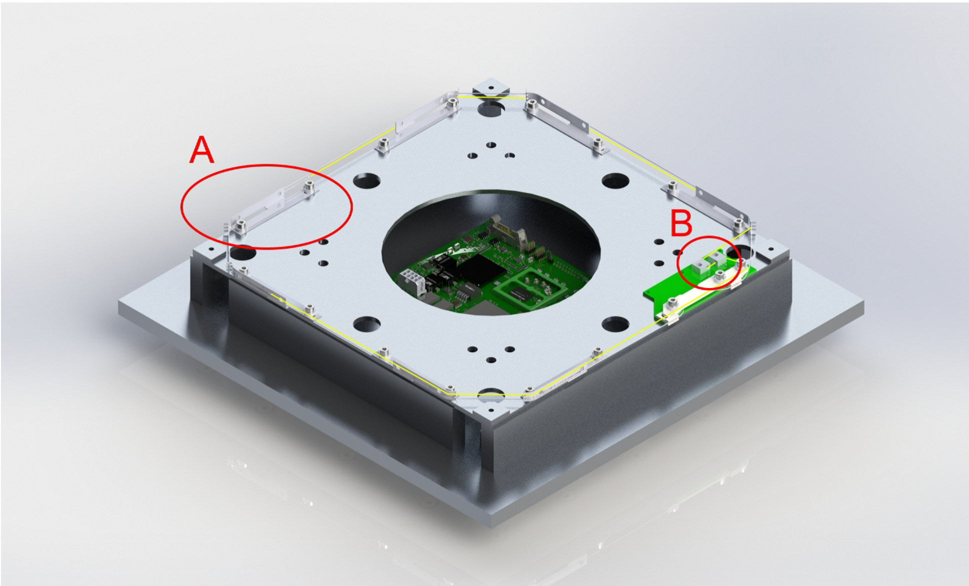

Figure 4.36: MGSE carrying SALSA EQM and VHF antenna demonstrator [104]. A – sheetmetal springs for VHF antenna deployment; B – redundant melting wire mechanism

As mentioned above, integration of the payload into an existing satellite bus was part of the SALSA project. TU Berlin's TUBiX10 bus was found to be the perfect fit for SALSA, especially because of the fact that a flight spare model of the S-Net constellation [105, 106] is available to be used as a flight model for SALSA. The TUBiX10 satellite bus includes all functionality that is needed for

SALSA except VHF antennas for assessment of the bands between 145 MHz and 175 MHz. Therefore, a VHF antenna system, including a deployment mechanism, was developed in a Master's thesis [104].

An MGSE was manufactured that can carry both the SALSA EQM board and the new VHF antenna system during verification (Figure 4.36). The system went through an extensive verification process, including functional, performance, shock, vibration, thermal, vacuum, EMC and radiation testing. All tests were conducted on equipment qualification level in accordance with European Cooperation for Space Standardization (ECSS) verification guidelines [107, 108], however tailored to small satellite payload requirements. The SALSA payload and VHF antenna system passed all tests with minor changes needed for the flight system. Required changes include fixation of the RF antenna connectors and an improved concept for antenna deployment under different temperature conditions. These adaptions and the future steps for SALSA are undertaken in a follow-up project that is described in the next sub-chapter. An MGSE was manufactured that can carry both the SALSA EQM board and the new VHF antenna system during verification (Figure 4.36). The system went through an extensive verification process, including functional, performance, shock, vibration, thermal, vacuum, EMC and radiation testing. All tests were conducted on equipment qualification level in accordance with ECSS verification guidelines [107, 108], however tailored to small satellite payload requirements. The SALSA payload and VHF antenna system passed all tests with minor changes needed for the flight system. Required changes include fixation of the RF antenna connectors and an improved concept for antenna deployment under different temperature conditions. These adaptions and the future steps for SALSA are undertaken in a follow-up project that is described in the next subsection.

4.5.3 Future implementation: SALSAT

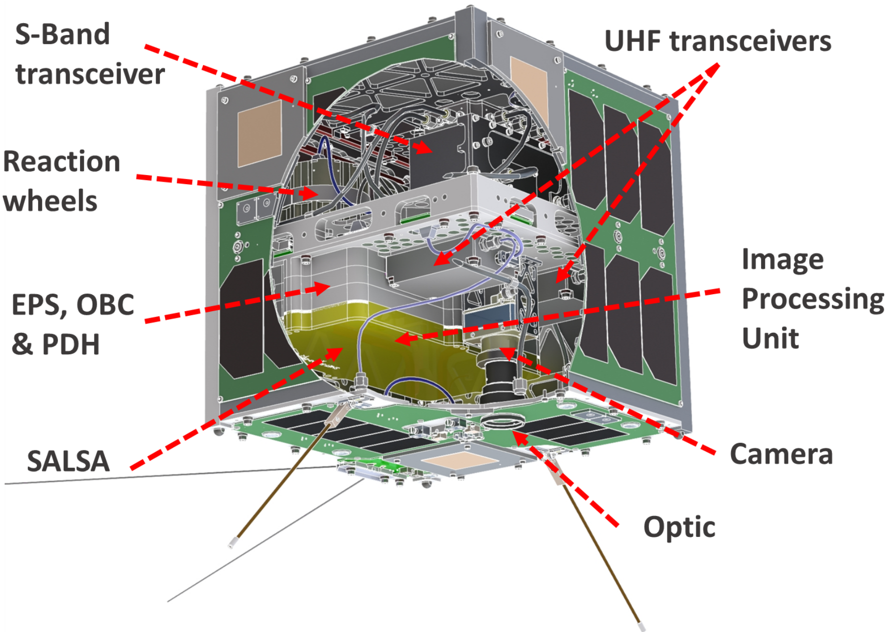

Figure 4.37: SALSAT artistic impression [109]

With project completion of SALSA, the development of a new VHF antenna system and the flight-ready TUBiX10 flight spare model, all requirements are given for a flight of the spectrum analysis payload. A follow-up project named SALSAT (Spectrum AnaLysis SATellite) was granted during which integration of SALSA into the satellite bus is conducted [109]. Besides SALSA and the new VHF antennas, two additional secondary payloads are added to the bus: a camera for simple attitude determination verification purposes and a fluid-dynamic actuator experiment that shall be verified for use in space [110]. Some additional hardware and software required changes of the satellite bus that became evident during the early flight phase of S-Net are also included in the project. The satellite's main components are shown in figure 4.37.

At the time of writing, the launch of SALSAT is scheduled for H1 2020. SALSAT will extend the results of MarconISSta, granting full global coverage of RF spectrum use on Earth and in LEO. In contrast to an ISS payload, the mission does not have the disadvantage of RF coupling losses and platform-dependant RF interference. Therefore, SALSAT presents the logical follow-up step to the already significant flight results of MarconISSta.

5 Summary & outlook

5.1 Summary

As mentioned in the introduction, this work is intended to discuss the following three aspects of small satellite systems:

- (RF) Characteristics and regulatory status of small satellites
- Investigation of current and potential new bands for small satellite operations
- Mission ideas and design of on-orbit spectrum analysis payloads that support frequency coordination efforts

The characteristics of small satellites were explained in the second chapter of this thesis with a focus on spectrum needs and communication capabilities. Small satellites are being launched into space more and more frequently, currently only constrained by the number of available launches and the early development status of some subsystems (mainly RF capabilities, attitude control and orbit control). Once these systems are more sophisticated, even more frequent launches must be expected. A tendency can be seen towards systems of the microsatellite class, as these can carry bigger and more capable payloads. Hundreds of these satellites, often as part of mega-constellations, are estimated to be launched in the near future.

While bigger satellites and mega-constellations will most probably use higher frequency bands for TT&C, the spectrum need in low frequencies (VHF, UHF, L & S band) will largely be driven by smaller satellite classes (picosatellites, nanosatellites). Their characteristics have been summarized as well as their regulatory treatment. The most eminent result of the assessment is that small satellites have to be treated as any other class of satellites to guarantee interference-free communication. Although small satellite developers tend to underestimate or even neglect frequency coordination activities, proper coordination is needed and expected to be undertaken by the developers (or operators).

The frequency coordination process for small satellites and the work flow of ITU-R and WRC were described in detail, followed by an overview of challenges for small satellite operators in this process and recommendations for simplified processes. Most importantly it was shown that small satellite operators are required to coordinate their efforts as early as possible. One cannot expect that the same coordination processes that worked in the past can be sustained in future missions as well. One important aspect is that the correct application of regulatory processes for small satellites has begun to be treated more strictly in the most recent years. For example, amateur-satellite bands can nowadays only be used by satellites that offer benefits for the amateur radio community. Another aspect is that the regulatory environment constantly changes. New allocations can be created, while the use of existing allocations can be constrained or allocations can be removed. Following ITU study group progress and reviewing the outcome of each WRC is strongly recommended.

The ITU studies on potential solutions for regulatory challenges were presented and discussed in chapter 3. To understand sharing studies, an introduction into sharing and compatibility studies was given, including interference scenarios for both ground stations and space stations. Given this background, the spectrum needs for small satellite TT&C have been assessed, taken into account the RF parameters of these satellites as well as protection criteria for the Space Operation Service. If 300 satellite systems are expected to be using frequency bands below 1 GHz for TT&C, having RF characteristics as explained in chapter 2, the required spectrum for uplink was calculated to be approximately 0.5–2.5 MHz and the required spectrum for downlink as approximately 0.5–1 MHz. It was also revealed that the existing spectrum for TT&C is expected to be sufficient for downlink, while for uplink new allocations are needed.

Extensive sharing and compatibility studies in existing TT&C bands and in the frequency ranges 150.05–174 MHz and 400.15–420 MHz have been undertaken between 2015 and 2019 (mainly not by the author, as explained in the relevant sections) and summarized in chapter 3. The frequency ranges were selected to be investigated since these were decided to be most probable for success during WRC-15. The studies show that the investigated bands for new allocations cannot accommodate any new users. However, the existing bands seem to be sufficient in the downlink direction, as mentioned above. In the uplink direction, it was found that there is spectrum that is allocated to TT&C, however not feasible for use by small satellites due to specific constraints. It was furthermore found that minor changes in the ITU Radio Regulations can make this spectrum available. This approach will be followed during WRC-19 negotiations.

In order to compare the studies and paperwork to the real sharing scenario, spectrum analysis mission concepts were drafted including ideas for tracking and localization of interferers. A first implementation was designed and developed during 2017 and 2018 as a spectrum analysis payload aboard the ISS, to be operated from August 2018 until February 2019. The development process was presented in chapter 4 along with preliminary flight results. These results indicate that the investigated bands are highly used, especially in Europe, North America and Eastern Asia. Due to the early flight status, final conclusions could not be drawn at the time of writing. However, the preliminary results already show the benefits of a on-orbit spectrum analyzer and further prove that the selected technology based on a LimeSDR can fulfill the functional requirements.

The limitations of the ISS experiments are the orbit and the forced integration of an RF limiter to not interfere with existing users of the VHF and UHF antennas. For this reason, a satellite payload for spectrum analysis that was built at TU Berlin is presented in this work, along with a concept for integration into the TUBiX10 satellite bus. Using a polar orbit, a spectrum analysis satellite mission can investigate spectrum use with full global coverage and without constraining RF limiters. A mission with SALSA as primary payload is scheduled for H1 2020.

5.2 Outlook

Part of the outlook are the final results of MarconISSta as well as the flight results of SALSAT. As more data becomes available, high resolution heat maps of global spectrum use will be created. Seasonal and daily deviations in spectrum use can be analyzed and frequency coordination will be supported by the flight results. It can already be concluded that the results of MarconISSta and SALSA will yield that the available spectrum is heavily used and more spectrum should be allocated. Another solution of regulatory problems could be found in improved sharing mechanisms. Two aspects are proposed to put into focus for future improvements of the regulatory environment.

Sharing feasibility and compatibility are mainly assessed by analysis of co-channel sharing. For this, protection criteria are used that are not always applicable to the examined systems. Worst-case sharing scenarios are taken into account with systems that have very high protection criteria, but almost no use cases in real-life scenarios. For example, sharing with sondes includes rocket sondes and drop sondes with antiquated spectrum needs which are only used in rare events or remote locations. Ten MHz of spectrum that is allocated for space-to-space TT&C are considered not feasible, although there are only two narrow-band users in the band. In other bands, existing users claim that the band is heavily used, although in reality there is scope for more systems (which can be assessed with on-orbit spectrum analysis). Co-channel sharing studies cannot represent the full picture of sharing feasibility. Additionally, the technical results of ITU studies are not always represented in the results of the World Radiocommunication Conferences. A conference will always include political and economic factors in decisions on regulatory changes. While the political and economic factors cannot be excluded from further coordination efforts, it is proposed to modify sharing and compatibility studies such that the real-life scenario is included besides co-sharing analysis.

An additional aspect of frequency coordination that should be reviewed is the way that spectrum is shared. In most satellite applications, spectrum is still coordinated by human spectrum managers in a comparatively static way. Spectrum is assigned based on first-come-first-served basis and existing users can comment on new intended use. A long coordination procedure is started with each ITU API and spectrum mangers of all incumbent users have to get in contact to discuss potential sharing. This process is not only lengthy, but also not satisfying for many LEO systems. The ITU only collects information on some orbit information, excluding the LTAN. If the LTAN changes over time (as in many systems), sharing of the same frequency by using different time slots (Time Division Multiple Access, TDMA) becomes difficult. TDMA can even becomes completely useless in the case that a satellite slip from one launch to another. As a piggyback payload, the small satellite developer cannot influence the orbit parameters of the new launch and in the worst case the LTAN will be different. Therefore, future coordination procedures should take the burden of insufficient coordination process from the human coordinator and instead introduce dynamic sharing algorithms into the system. Modern SDR systems can investigate current use of a pre-defined portion of the spectrum (as it is done in MarconISSta and SALSA). Based on this, the system could identify currently unused channels and use these temporarily. Terrestrial systems have used similar algorithms for many years. Small satellite transceivers were built in a simple way, however with more complex systems, the introduction of cognitive radio into small satellite bands should be investigated.

From an educational point of view, the field of frequency coordination should be more deeply integrated in the curriculum of space engineering programs. The wrong application of ITU procedures by small satellite developers has to be prevented by enhanced dissemination of knowledge. Besides universities, the ITU and national administrations should put focus on improved handbooks, tutorials and seminars on the right application of filing processes.

The author's future work will focus on the continued support of ITU study groups as well as on new methods for more efficient spectrum use. A second phase of the MarconISSta experiment is planned as well, introducing new applications like software-defined radio blocks that can test and verify the above-mentioned methods on dynamic spectrum use in space.

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Appendices

A MarconISSta part list

This list includes all parts that have been uploaded to the ISS for the MarconISSta experiment.

Figure A.1: MarconISSta parts (some stowed in bubble wrap bags) ready for launch

Part	Mass [kg]	Dimensions [cm]
LimeSDR (+ Housing) *main component*	0.392	15 x 8.5 x 2.8
RF Coupler *necessary to integrate MarconISSta in existing ARISS setup*	0.138	7 x 6.2 x 2
2 SMA-m to SMA-m cables *connection between LimeSDR and coupler*	0.124	100
SMA-m to N-m cable *connection between ARISS transceiver and coupler*	0.194	300
SMA-m to N-f cable *connection between LimeSDR and adapter*	0.130	200
N-m to D3899 adapter cable *connection to proprietary RF cable port*	0.100	100
USB-m (2x) to USB-f Y-cable *cable Astro Pi to LimeSDR*	0.050	33
USB-m to USB-f extension cable *extension cable for LimeSDR auxiliary power supply*	0.186	450
3 Micro SD 32 GB Cards *contain Raspbian OS for Astro Pi*	0.006	1.5 x 1.1 x 0.1
SD Card Adapter *in case that Micro SD cards need to be used on laptop*	0.001	3.1 x 2.4 x 0.2
2 RF Limiter *to prevent high power inputs to LimeSDR*	0.016	3.6 x 1.0 x 1.0
Adapter N-f to SMA-m *connection to existing VHF/UHF N-m cable*	0.026	3.1 x 1.8 x 1.8
50 Ohm dummy load *optional component to close open connectors*	0.003	1.5 x 0.9 x 0.9
SMA Torque Wrench *tool to fasten SMA connections*	0.082	16.5 x 1.5 x 1.4

Table A.1: MarconISSta part list. *-f* /*-m* denotes *female*/*male* connector. Overall weight is less than 1.5 kg.

B MarconISSta CAD drawings

The following CAD drawings show the work of the student team in charge of the MarconISSta structure. The team led by C. Jonas developed the housing based on the Astro Pi design.

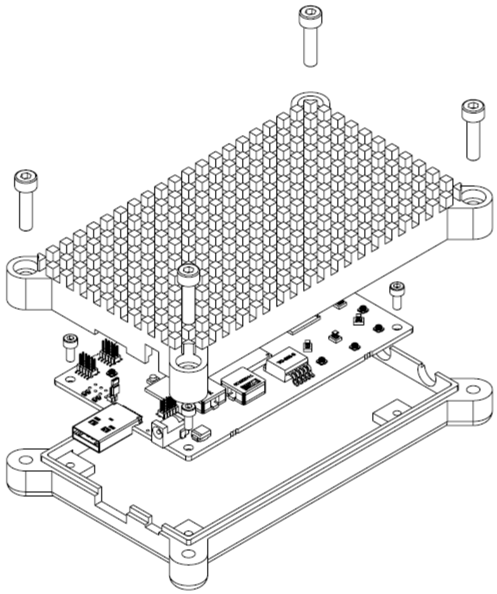

Figure B.1: MarconISSta CAD overview [74]

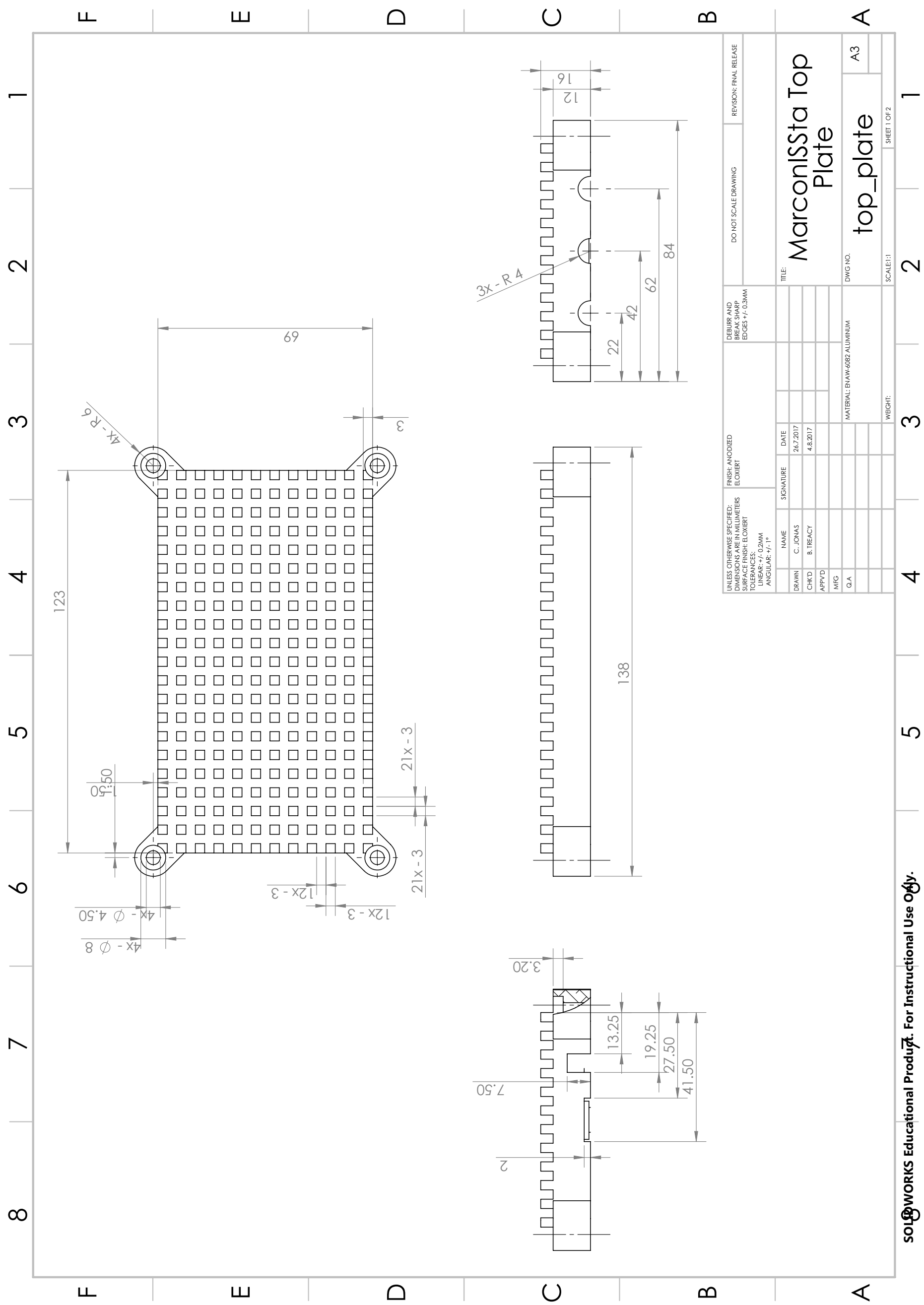

Figure B.2: CAD of MarconISSta top plate

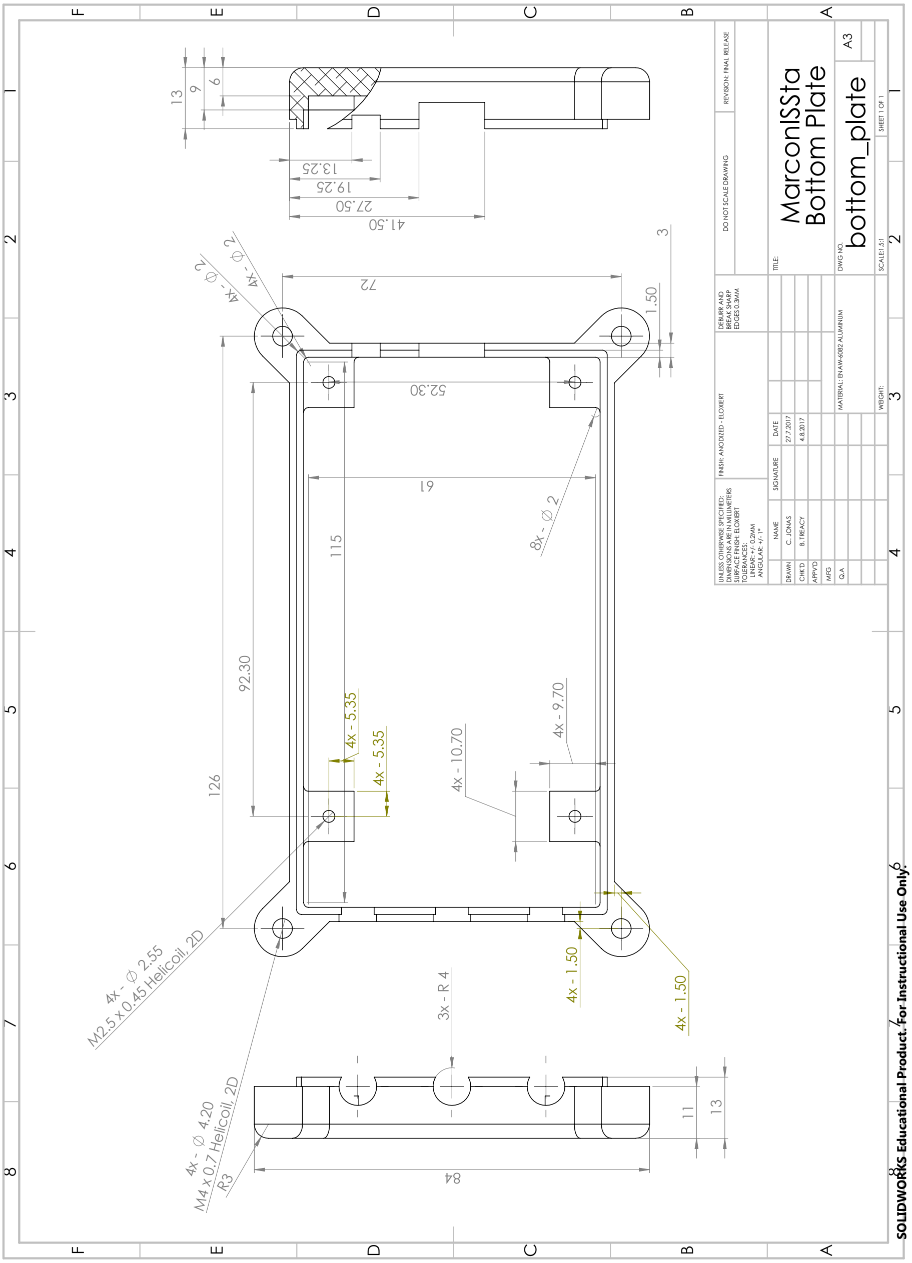

Figure B.3: CAD of MarconISSta bottom plate

C MarconISSta code snippets

Most of the software implementation was developed by a student team. The code snippets below show the code snippets that allow automated operations of MarconISSta.

Raspbian Operating System background service for MarconISSta (implemented by L. Gräfje):

```
[Unit]
Description=MarconISSta's start stop script which controls the experiment with a set timetable

[Service]
ExecStart=/opt/marconissta/script.sh /etc/marconissta/timing.txt soapy_power

[Install]
WantedBy=multi-user.target
```

Script to schedule and initiate experiment runs (implemented by L. Gräfje):

```
#!/bin/bash
# Author: L. Graefje
# This script is used to start and stop a recording at some specified time
# points. These time points are read from a file called "timing.txt" in the
# current working directory. Each line in this file should consist of two dates
# that can be understood by date(1). The rest of the line will be passed as
# arguments to the spawned process. The spawned process is given as a command
# line argument to this script.

if [[ $# -ne 2 ]]; then
  echo "Usage: $0 timing-file startcommand"
  exit 0
fi

TIMEFILE=$1
STARTCOMMAND=$2

while
  while read start stop options; do
    STARTSECONDS=$(date +%s -d $start)
    STOPSECONDS=$(date +%s -d $stop)
    NOWSECONDS=$(date +%s)
    IFS=' ' read -a args <<<$options
    echo "STARTSECONDS: " $STARTSECONDS
    echo "STOPSECONDS: " $STOPSECONDS
    echo "NOWSECONDS: " $NOWSECONDS

    # basic error checking
    if [[ $STARTSECONDS -ge $STOPSECONDS ]]; then
      echo "WARNING: invalid interval (stop before start)"
      continue
    fi

    if [[ $STOPSECONDS -le $NOWSECONDS ]]; then
      echo "WARNING: interval is in the past. Skipping"
      continue
```

```
    fi

    if [[ $STARTSECONDS -le $NOWSECONDS ]]; then
      echo "WARNING: start time tag in the past"
    else
      # wait until the start date if it is not in the past
      sleep -- $(($STARTSECONDS - $NOWSECONDS))
    fi

    # start the subprocess
    echo "executing $STARTCOMMAND ${args[@]}"
    $STARTCOMMAND "${args[@]}" &
    PID=$!

    # wait until  the end date
    NOWSECONDS=$(date +%s)
    echo "NOWSECONDS: " $NOWSECONDS
    sleep -- $(($STOPSECONDS - $NOWSECONDS))

    # finally, terminate the sub process
    echo "Kill process again"
    echo "kill $PID"
    if ! kill $PID 2> /dev/null; then
      # if kill did not terminate sucessfully, we assume that the process died by
      # itself which would not be good since we did not expect it
      echo "WARNING: child process died before we could kill it"
    fi
  done < $TIMEFILE;
sleep 10m; do :;
done
```

Snippet of exemplary timing file (implemented by L. Gräfje):

```
[...]
2018-09-07T18:00:00 2018-09-07T18:59:00 -d driver=lime,soapy=0 -c -f 1263M:1266M -C 0 -A LNAH -r
      5000000 -G LNA=30,PGA=9,TIA=3 -O /var/marconissta/week04/2018-9-7T18-0-0_L_HIGH.csv
[...]
```

First two lines of resulting CSV file, generated by Soapy Power software:

```
2018-09-07, 18:00:27, 1262000000.01, 1266999999.99, 9765.62496281, 820080, -132.484, -132.657,
      -132.652, -132.454, -131.857, -131.283, -130.889, -131.142, -131.81, -132.148, -131.838,
      -131.467, -131.573, -131.858, -132.129, -131.964, -131.913, -131.838, -131.65, -131.329,
      -131.154, -131.163, -131.529, -131.606, -131.206, -130.77, -130.597, -130.799, -130.914,
      -130.753, -130.346, -130.193, -130.607, -130.649, -130.511, -130.227, -129.699, -129.424,
      -129.091, -128.919, -128.939, -129.141, -129.424, -129.844, -130.033, -129.87, -129.351,
      -128.819, -129.077, -129.595, -129.265, -129.029, -129.384, -129.757, -129.407, -128.98,
      -128.851, -129.12, -129.422, -129.28, -129.198, -129.289, -129.058, -128.57, -128.489,
      -128.515, -128.914, -129.107, [...]
2018-09-07, 18:00:31, 1262000000.01, 1266999999.99, 9765.62496281, 820080, -132.718, -132.757,
      -132.674, -132.727, -132.676, -132.57, -132.541, -132.601, -132.554, -132.49, -132.399,
      -132.474, -132.396, -132.46, -132.393, -132.351, -132.312, -132.099, -132.021, -131.977,
      -131.788, -131.788, -131.702, -131.693, -131.731, -131.578, -131.354, -131.137, -131.288,
      -131.281, -130.935, -131.05, -131.2, -131.242, -130.81, -130.781, -130.817, -130.802,
      -130.62, -130.584, -130.615, -130.398, -130.353, -130.434, -130.473, -130.438, -130.364,
      -130.26, -130.163, -130.118, -130.079, -129.89, -129.866, -130.066, -129.887, -129.646,
      -129.859, -129.805, -129.859, -129.8, -129.574, -129.697, -129.599, -129.687, -129.675,
      -129.773, -129.628, -129.486, [...]
```

Exemplary plot of a measurement:

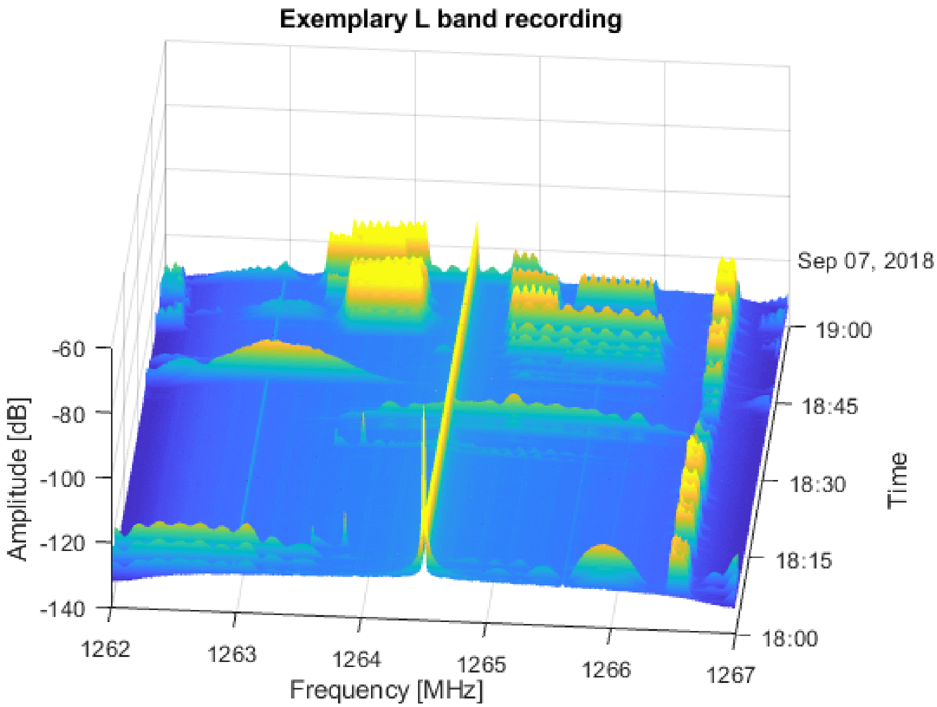

Figure C.1: Exemplary visualization of a 1-hour measurement in L band

D SALSA EQM pictures

SALSA EQM board. Schematics and board layout were created by J. Großhans, systems engineer of the SALSA project (based on LimeSDR).

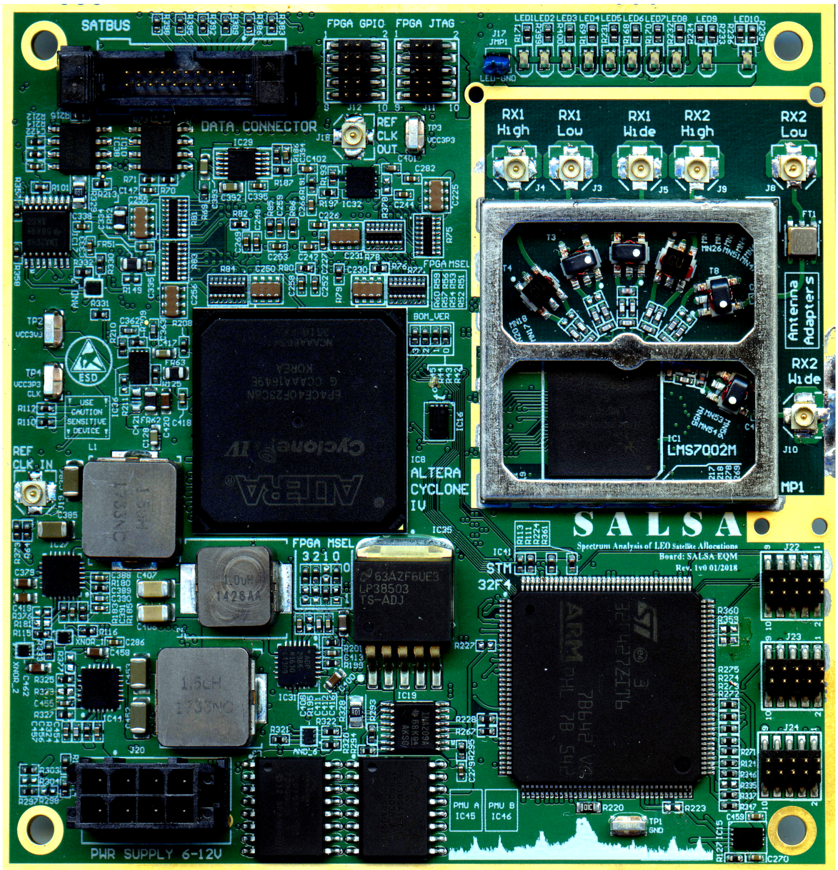

Figure D.1: SALSA EQM top view [103]

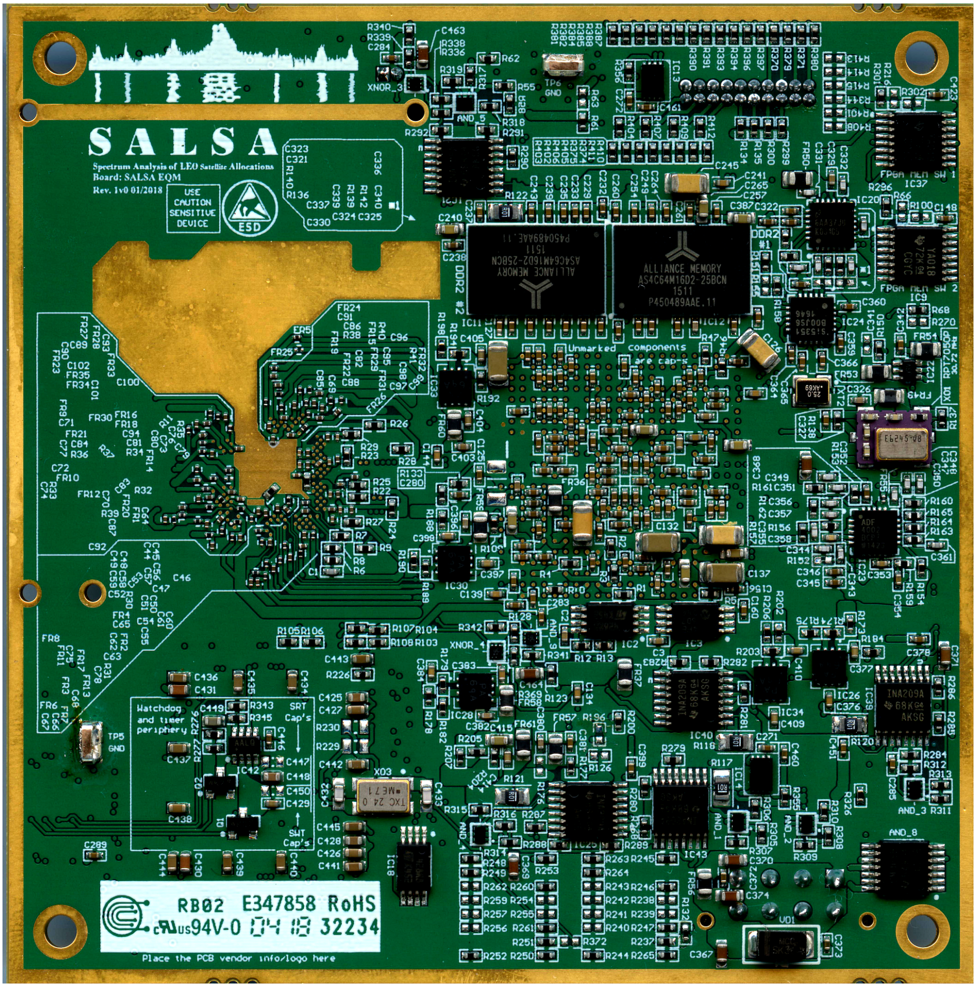

Figure D.2: SALSA EQM bottom view [103]

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Investigations on the current and future use of radio frequency allocations for small satellite operations

Global radio frequency spectrum use for satellite communication is a present-day challenge that has been aggravated by the increased launch of small satellites during the past 15 years. This thesis aims to examine both regulatory and technical aspects of spectrum use. The focus of this examination is on frequency bands that are commonly used by small satellites and on those bands that might be applicable for future use. The thesis content is subdivided into three parts. The first part presents the needed background on small satellites as well as the regulatory environment for small satellites. The second part gives insight into the results of a theoretical assessment of current and future small satellite allocations. The third part depicts two concepts for on-orbit spectrum analysis applications which allow the analysis of the problem from the technical side, including first flight results.
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