Design and AIV of Ongoing ISS Based Student Project for Analysis of RF Spectrum Utilization

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ABSTRACT
MarconISSta is a spectrum analyzer installed on the International Space Station to analyze frequency use in various frequency bands from VHF to S band. This data will provide vital information for the frequency coordination of future missions and might prevent harmful interference by providing up-to-date information throughout the operational period of the payload. To minimize cost and time the project uses a NewSpace and commercial off-the-shelf (COTS) approach. This project was developed by scientific staff and students of Technische Universität Berlin (TU Berlin).

The MarconISSta payload utilizes a software defined radio (SDR) named LimeSDR as the spectrum analyzer. It is connected to the “Amateur Radio on the ISS” (ARISS) antennas while allowing for simultaneous operation of normal ARISS equipment and MarconISSta without interference. The data collected over the mission duration is downloaded in chunks and later analyzed on ground to investigate current use of the frequency bands and potentially aid in frequency coordination. The SDR based technology is first tested aboard the ISS and will later be used in a small satellite mission planned for 2020.

This paper will present the design steps, assembly, integration and verification. Further, it highlights challenges and lessons learned during the student project.

INTRODUCTION
Most satellites, regardless of their task, need to establish a two-way communication with a ground station on earth to control the satellite and download its data. The existing frequency bands for satellite communication were allocated based on an outdated prediction of the number of operational satellites. The reasoning for this assumption is a IEEE forecast of satellite launches which shows that future launches will to a large extent carry small satellites.1 This increases the probability of harmful frequency interference especially in the lower bands such as Very High Frequency (VHF), Ultra High Frequency (UHF), L band and S band, as these satellites predominantly use lower bands due to low hardware cost, pointing requirements and power needs. The MarconISSta payload is therefore installed on the ISS with the goal of analyzing usage of these frequency bands and frequency “hot-zones”. This data could be used by different satellite operators or the International Telecommunication Union (ITU) to find the right frequency for the right mission, while being able to account for current usage and predicted interference. The payload was uploaded to the ISS in May 2018.

MarconISSta is derived from the Italian word ‘Marconista’ meaning radio amateur. The main objective of the MarconISSta payload is to analyze frequency traffic in different spectral bands such as VHF (145.8 – 146 MHz), UHF (435 – 438 MHz), L-Band (1260 – 1270 MHz), and S-band (1270 – 2400 MHz). The heart of the payload is a COTS component named LimeSDR (SDR: Software Defined Radio). While the device can generally be used for multiple applications like transmitting and receiving signals as a reconfigurable, software defined radio, in this project it will be used to analyze the spectrum use in various bands. Data handling is performed by an already onboard Astro Pi, a special radiation hardened version of the COTS microcomputer Raspberry Pi. The Astro Pi was successfully used in earlier educational missions and has had software upgrades further increasing safety and reliability since the beginning of its operation2. This unit acts as the payload data handling system.
(PDH system) which processes all the data and stores it in its SD card for further download. Power for both devices is supplied by a 5 V Multi-port Universal Serial Bus (USB) power source installed on the ISS. Currently, an ARISS VHF transceiver is being used with the ARISS antennas, so MarconiISSsta is connected to the ARISS antennas through a coupler to enable simultaneous use of both systems.

This project evolved at Technische Universität Berlin (TU Berlin). The team consists of 13 students, some of which had a background in aerospace engineering, some came from other fields like mechanical engineering, computer science or electronics engineering. The team was guided and advised by scientific staff from TU Berlin. This paper is dedicated to the organization within the project group and the several challenges students faced during the course of the project. The design and the coordination with suppliers and manufacturers were carried out by students. Furthermore, they carried out the verification of the payload including writing test procedures, test reports, documentation and testing the payload at different test facilities. Through the extensive involvement of students in the project, much valuable first-hand experience was gained by every project member. Students learned how real scientific missions transpire, how governmental agencies such as the European Space Agency (ESA), the National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR) operate and how to comply with the rules and regulations of the various space standards.

**MOTIVATION**

Currently institutes, organizations and private users are struggling to find usable frequency to communicate with their satellites. This has become one of the biggest hurdles in the space system design. MarconiISSsta was born to aid in frequency coordination by making mission planning and frequency allocation easier and more efficient. To achieve this, MarconiISSsta supplies a heatmap of “hot-zones” around the globe in different frequency bands, giving mission planners and administrations the data needed to choose the right frequency for the right mission. None of the students worked on projects for the ISS before, so it presented many new challenges and growth opportunities for both those familiar and unfamiliar with the space sector. For many, the project served as a starting point in their space career wherein they got a chance to work with different space organizations and learn of what meeting their high standards and requirements meant. These are the key motivations that made students work diligently for 8 months straight, in addition to their regular studies and student jobs. Aside from frequency coordination, educating students and giving them this unique opportunity to gather practical experience and bring space and the ISS just a little bit closer was an equally important objective throughout the course of this project. It will equally continue to be a focus in the coming months, as data from the ISS becomes available and will require on-ground processing and analysis.

**STUDENT COORDINATION**

MarconiISSsta is product of collaborative work from scientific staff and students at TU Berlin, Germany. A total of 17 members worked on the project in which 13 were students with different nationalities and expertises. The project started in early 2017 and is planned to be completed in late 2018.

The student part of the project was kicked off during the summer of 2017. In the initial meeting the project manager allowed the students to form teams based on their interests and expertise. There were three teams formed: structures, software and verification. Some students had overlapping expertise, so they participated in multiple teams. The structures handled all the design of the LimeSDR casing, designing and 3D printing parts, ordering hardware and finalizing the layout and mounting mechanism of components on the final board which is installed on the ISS. The software team was tasked with writing and integrating software on the Astro Pi. Finally, the verification team took responsibility for identifying necessary requirements from given documents, tests, test facilities, test levels, test plans, test procedures and test reports.

Most of the students were working part time on this project in an extracurricular capacity. To maintain proper communication within the team regardless of irregular working hours and meeting times, multiple approaches were reviewed and analyzed. Many options and tools existed, many of them digital. In the end GitLab was chosen to manage issue tracking and allow for version control of the software and documentation. The GitLab is hosted on a university server. This platform allowed different teams to work simultaneously while still making the work done accessible to other teams. In addition to the GitLab, a folder structure and naming convention was defined to achieve consistent documentation of work done. The top-level folders and the content included within them is shown in Fehler! Verweisquelle konnte nicht gefunden werden. A main focus on data in the git was to allow students to find guides and introductions to topics foreign to them, allowing them to ease into the project and learn as much as possible. Additionally, work done was displayed in a very transparent fashion. For example, the git contained verification test reports and documents such as the flight safety data package.
(FSDP) that were signed and submitted to agencies such as ESA.

Figure 1: Folder structure within git

Work orders were posted in a so called “Issue” on the GitLab. The issues have a responsible person, a criticality, task description, deadline and the possibility for people to discuss the issue at hand. Often, other team members would chip into issues and add their own ideas and expertise, giving the assignee some pointers or solutions to problems. Due to this tool being web-based the entry barrier for working with it was very low, keeping the participation of team members consistent, despite the extracurricular nature of the project. To recapitulate work done and inform the team of news, every week team meetings took place on Wednesday’s from 6pm to 8pm after the class hours. The project leader would discuss updates, inform of changes and his progress in getting approval from the various organizations. Additionally, every member would present his current status and receive input from other members and the project. At the conclusion, the work statements and issues were re-evaluated, changed if necessary or supplemented by adding new ones to the GitLab.

The coordination proved to be very successful and a high attendance at the weekly meetings was achieved. Despite the project leader’s strict instruction “University first, ISS second”, many students took the time to attend and participate in the project and meetings. Thanks to the meetings, everyone received exposure to different fields and challenges of the project, even if they did not actively work on them.

DESIGN APPROACH

**Mechanical Design**

MarconISSta payload consists of three main components and attaching parts. The three main components are LimeSDR, Astro Pi and radio frequency (RF) Coupler. LimeSDR is a COTS SDR which has the ability to transmit and receive radio signals in VHF, UHF, L and S Bands. However, MarconISSta will only be receiving data and will not be transmitting. The LimeSDR does not possess any protective casing to shield itself from any (unintended) damage. Therefore, the structures team designed an aluminum casing for the device. During the design phase of the housing high operational temperatures at the core of up to 70 °C were noticed. This conflicted with the maximum allowable surface temperature of 45 °C according to the crew safety standard. Accordingly, proper heat dissipation was one of the major constraints during the design of the housing. The other constraints involved material compatibility, non-flammability, manufacturability, and of course the price. Ultimately, the final design consisted of two aluminum casings (top and bottom) split in half. The bottom casing had four pads to mount the LimeSDR and also acts as a grounding path for any electrical surcharge developed onboard. To ensure the temperature is within the allowable limit, the outer surface of the upper half of the casing includes an array of cubes. These cubes increased the surface area for heat dissipation and kept the temperature within acceptable limits. The design of housing was finalized through rigorous iteration, accompanied by thermal simulations and testing. The aluminum housing was manufactured in house. Four screws secure the LimeSDR within the housing, while an additional four screws connect the two halves. Outlets for RF connectors, USB connection and an additional power source were included in the design. This is as shown in Figure 2. Furthermore, to comply with the other crew safety and hazard requirement all the sharp edges were rounded off. Additionally, the surface of the housing was anodized to increase corrosion resistance and further decrease the electrical conductivity.
To supply power and control operations, the LimeSDR is connected to the onboard Astro Pi via a universal serial bus (USB) type A male connector. The housing of the Astro Pi and the MicroSD card contained within are already existing and not within the scope of this project. It was already uploaded during ISS increment 46/47 as part of ESA astronaut Tim Peake’s mission after which it was kept on-board and is therefore not part of the final cargo.\(^2\)

Data is received through the ARISS antennas already present on the ISS. There are currently three antennas installed on the COLUMBUS module for ARISS operations: one VHF/UHF antenna and two L/S band antennas. The VHF/UHF antenna is used for amateur radio operations. ISS crew can use the transceivers to communicate over these frequency bands with people on earth. However, MarconISSsta requires use of these antennas for the fulfillment of its primary objective. An RF coupler is therefore added to the system and MarconISSsta is attached to the coupled ports which allows simultaneous operation of the antennas by both ARISS’ systems and MarconISSsta. As ARISS transmission power can be as high as 50 dBm which would harm the LimeSDR, a RF limiter is added to the system which limits the power to 12 dBm\(^4\). One of the two L/S band antennas is currently not used for ARISS operations, which make it available for MarconISSsta. Accordingly, the L/S band port of the LimeSDR can be directly connected to the antennas without the use of a coupler.

Other uploaded peripherals include RF cables, MicroSD cards and a torque wrench. Most of the cables present are made of polyvinyl chloride (PVC) which is categorized as flammable material in the JSC 29353A standard document.\(^6\) Therefore, these cables are wrapped with fiberglass tape as per the procedure provided within the same document to make them fire resistant. The sub-miniature version ‘A’ (SMA) torque wrench is used to assemble and disassemble the SMA cables on to the LimeSDR. The wrench has a maximum torque capability of 8 in-lbs is added to ensure the safety of the MarconISSsta payload from crew over/under tightening the connectors which could lead to malfunctions of the system.

**Configuration and Assembly**

The final configuration is as shown in Figure 3. Blue lines/fills represent components sent to the ISS, while white components are already present. The LimeSDR has a total of five ports, out of which three are RF female SMA connectors, one is a USB type a male connector and one is a direct current (DC) power input jack. Out of three RF female SMA connectors two are connected to the coupler through RF cables wherein the RF limiters are installed on the LimeSDR end. The other SMA connector interfaces with the L/S Band antenna through a separate RF cable which is currently not used by any systems on the ISS. Both power and data transmission are achieved through a single USB port. The herein before mentioned DC input jack is not used as it would need a proprietary power source on the ISS which would have made safety processes more complex. To supply enough power through the single USB port a Y-cable splitter is used, connecting the data lines to the Astro Pi and power lines to the existing USB charger. Since the Astro Pi is also powered by this USB charger, the grounds and power lines of the two have identical electrical potentials.

The RF Coupler serves as an interface between the ARISS system, VHF/UHF antenna and MarconISSsta, while maintaining the safety of all connected systems. As explained earlier the MarconISSsta payload is connected to the coupler using the RF cables. In case one of the coupler ports are not used, a 50-ohm impedance terminator load is applied to prevent any damaging feedback. Currently, no cable exists on the ISS which can connect the coupler and the VHF/UHF antenna. Therefore, a RF cable male SMA connector on the coupler end and N-type connector on the transceiver end is uploaded with MarconISSsta.
Figure 3: Configuration of MarconISSSta payload

The individual components are wrapped in foam package and are placed in a 0.5 cargo transfer bag (CTB) which carries the payload to the ISS. This is shown in Figure 4. The whole assembly is mounted on a 254 mm x 254 mm plate which is available on the Columbus module of ISS using Velcro. This is as shown in Figure 5, which was carried out at the European Astronaut Centre (EAC) in Cologne. The entire assembly will be carried out by a crew member on the ISS.

Figure 4: MarconISSSta payload placed inside a 0.5 CTB

VERIFICATION AND TESTING

Verification of MarconISSSta

TU Berlin is one of the leading pioneers in developing small satellites for educational and scientific purposes. It has 16 satellites under its belt, nine of them active as of April 2018. Despite MarconISSSta being the first ISS based system by TU Berlin, much knowledge and expertise of verification and testing could be adapted. However, it is important to note that especially ISS requirements vastly differed from conventional satellites. Therefore, the verification and testing of the payload was comparatively challenging as not only different conditions had to be tested but some of the tests had stricter requirements.

As MarconISSSta was developed in an educational environment (i.e. at the university with governmental/agency funding), it had limited resources to work with. For this reason, a protolflight philosophy was adapted. To reduce the risk that emanates with this model philosophy, two protolflight models were used wherein one acted as a fully qualified flight spare. Airbus S.A.S. is responsible for integration of systems in the ISS COLUMBUS module and provided the interface requirements. Therefore, MarconISSSta worked with Airbus in finalizing the verification matrix, which provides information on which tests are required for the payload. The verification team was responsible for providing evidence and justification on why a particular verification method is necessary or a different one is obsolete for qualifying the system with the limited budget available. For qualification the following physical tests were carried out: vibration, electromagnetic compatibility (EMC) and touch temperature test. The rest of the requirements such as material specification, flammability, sharp edges, identification labelling, functional test etc. were verified through analysis, inspection and review of design. The three
physical tests were necessary as the LimeSDR did not have any flight heritage. Vibration tests would identify if the system can withstand the stresses during transport and launch. The EMC test confirmed the system would not emit or conduct any harmful radiation which would harm the crew or other systems of the ISS while the touch temperature test verified the systems surface temperature would stay below 45 °C to prevent fire and harm to astronauts, even during the worst-case conditions.

Testing of MarconISSta

As explained in the earlier section, three physical tests were carried out. Touch temperature test was carried out in house. The setup is as shown in Figure 6. Testing occurred with ambient temperatures of 22 °C to 35 °C. The ambient temperature on the ISS is around 24 °C and can reach up to 35 °C, however this is unlikely. The LimeSDR was placed in a thermal chamber and was powered through an external power source which was placed outside the test chamber. Two temperature sensors were attached to the LimeSDR which provided information throughout the test period of two hours. The temperature of the LimeSDR stabilized at 40.6 °C at 35 °C ambient, while at 22 °C ambient the temperature stabilized at 25.8 °C. This provided evidence that the system’s temperature will not cross 45 °C even in the worst ambient conditions.

Figure 6: Touch temperature setup in thermal chamber

Vibration tests for a conventional satellite consist of a hard mount on a shaker table, where different levels are applied and the response is observed. However, for MarconISSta the vibration test was comparatively different, as the whole system is transferred to the ISS through the CTB. Testing took place before finalization of the CTB content, therefore the payload was wrapped in bubble wrap to simulate the CTB. The wrapped payload was then placed in a wooden casing that did not leave space for extensive movement to simulate the real configuration inside a CTB. It was then hard mounted to the shaker table as shown in Figure 7. The test levels and test procedure were derived from the SSP50835 document which is specific to payloads carried to the ISS. Out of the various vibration test available, only the random vibration test along with modal survey was applicable for the payload. The resonance search was carried out between 2 Hz and 2000 Hz with a sweep rate of 2 oct/minute and 0.5 g acceleration. The random vibration test was carried out with the overall test level of 9.47 G\text{rms} which is equivalent to the max flight envelope. The test was carried out in three different directions (X, Y and Z axis) between which a resonance survey was carried out to record the responses before and after the high level of vibration. Accelerometer sensors were applied to three different coordinates of the LimeSDR which picked up the vibration responses and displayed it on workstations placed outside the chamber. Pass/full criteria for the random vibration response level was less than the input envelope. The test was carried out at vibration test facility at Astro- und Feinwerktechnik GmbH Berlin (Astrofein), Germany. Both modal survey and random vibration test was successfully passed, as MarconISSta conformed to the criteria mentioned before.

Figure 7: Vibration test setup at Astrofein

The EMC test was carried out at an ArianeGroup S.A.S. facility in Bremen, Germany, taking two days in total. Unlike the vibration test which is a component level test, the EMC test is carried out on a system level. For EMC testing, the whole system was setup on an Electro-Static Discharge (ESD) table which is present in an acoustic chamber. The test setup is as shown in Figure 8. The system is operated remotely outside of the acoustic chamber. Different tests verify that the system does not emit any harmful fields, is not
susceptible to breakdown due to ambient fields and does not couple in a way that would cause damage. A total of four different test types were carried out: radiated electric field susceptibility, radiated magnetic field susceptibility, radiated electric field emission and radiated magnetic field emission. During testing, the system is operated and any occurring anomalies are recorded. Pass/fail criteria are the occurrence of anomalies in operation or detection of harmful emissions. The test levels and test procedure were extracted from the Columbus ESA requirement document COL-ESA-RQ-14. Different antennas (vertical polarized, conical, Biconical, DRG) were used to generate different levels of frequencies for the different experiments, the lowest being 14 kHz and the highest being 10 GHz. These frequencies and configurations were based on the test levels specified in the COL-ESA-RQ-14 document. At the end of the test all four-different test configuration passed as there were no anomalies detected from the system under load and the system was not damaged.

![Image](image.png)

**Figure 8: EMC test setup (9)**

**DOCUMENTATION**

Any project, be it a satellite or an ISS payload requires extensive documentation. Beyond design and implementation, sustainable engineering and traceability play a vital part that is reflected in a project’s documentation. Through documentation the organizations accepting MarconISSta on the ISS can see what it consists of, how it is realized, how it is tested etc. It is therefore used as the basis for agreements of cooperation.

Due to multiple parties (i.e. NASA, ESA, DLR, ARISS…) being involved in this project, the documentation had to conform to the requirements of all involved. This proved to be a unique experience and a challenge for the students. Through documentation the magnitude of the work done became evident. Within MarconISSta each document had responsible student to create it, or at the very least a student involved in creation. Students had the responsibility of delivering a document that did not only conform to university standards, but also to the standards of the involved parties. This was achieved through reading numerous standards and documents released by the involved parties and taught students how to best interact with these documents and where to best find information. The firsthand experience gained in this live project will be invaluable to the students in future missions.

Students supported and created various standard documents such as the FSDP, acceptance data package (ADP), verification control plan, vibration test procedure, EMC test procedure, touch temperature test procedure and report, hazard report, software plan, label plan and operational manual.

In addition to official documentation that was submitted to the governmental agencies or used internally, a web presence in the form of a blog was also created. It was updated by a student throughout the course of the project. When new milestones were reached such as approval by a certain organization or successful testing a new blog entry was created. The focus lied on highlighting the student involvement while sharing with the international community the status of the project. Additionally, the blog features a list of team members with a short bio and a gallery page with non-critical internal photography showcasing various work in progress steps of MarconISSta.

Public outreach campaigns such as this are typical for student projects, especially those funded by national agencies such as the DLR. They further help motivate the students by giving a sense of recognition for work done.

To identify the project better, a dedicated logo was also created by the students, as shown in Figure 9. It is used across public documentation such as the blog or Conferences and on MarconISSta items.
LESIONS LEARNED

During the course of project there were several lessons learned by the students. A few of them are summarized in the following paragraphs.

First and foremost, the act of working together as a team in a project of this scale and significance was new for many students. Often, small hands-on projects are part of the curriculum, but working in a big team, throughout the course of a year and having to conform to the requirements of industry and agencies rather than the class’ grading scheme made this a new experience for many. Learning that deadlines can often not be extended, that requirements are absolute and that often times there is no in-between pass and fail helped shape the student’s understanding of requirements as they exist in the world beyond the university.

As mentioned in the previous paragraph, the size of the project group was new for many students. Coordinating and communicating effectively in big teams without supervision every step along the way was a lesson learned early on. The importance of proper work tracking, work documentation, advice communication and keeping in mind sustainable engineering were revealed to the students.

One of the other considerable lessons learned is proper documentation in the GitLab repository. Initially, it was quite chaotic and finding the right document often cost several minutes to hours. Therefore, not only creating a proper structure at the start of the project but maintaining it throughout the project is very important in avoiding loss of time. Additionally, it became evident with the creation of documentation for the involved parties that all the work done must be documented thoroughly, as otherwise it is hard to comprehend why some choices were made, why parts look the way they do etc.

As mentioned previously, not every student came from an engineering background. For some, engineering disciplines such as computer aided design (CAD) or programming were new. Through the practical work done within the project students have strengthened their technical skills and understanding of a real product’s development cycle, i.e. the path from a raw concept, the CAD design, manufacturing, testing and use.

FUTURE WORK

As of April 2018, the analysis of the recorded data is being prepared and tools for storage and processing are being developed. After increment 57 the payload will be handed over to the ARISS team for subsequent use.

MarconISSta is bound to the ISS’ orbit, the schedule of the Antenna usage and slots for data download. To circumvent these restrictions, TU Berlin is developing a small satellite with similar functionality, but with a different orbit and longer mission lifetime. This will not only aid different users such as other satellite manufacturers, but also support the ITU in frequency allocation for future missions. The launch of the satellite is currently scheduled for 2020.

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