SPACECRAFT BEACONS: RADIOCOMMUNICATION APPROACHES TOWARDS INTEROPERABLE AUTONOMOUS SELF-IDENTIFICATION AND TRACKING

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ABSTRACT

The ongoing smallsat (r)evolution characterised by strongly increasing numbers of launches, failures, and reduced sizes not only raises issues regarding the detection and identification of space objects for the overall Space Situational Awareness (SSA), future Space Traffic Management (STM), but also for the individual spacecraft operators themselves. This paper gives an overview of the challenges and proposed tracking aids for spacecraft and debris, focussing on active radiocommunication solutions. Following the motivation for beacon transmitters, the known approaches to date will be discussed. Furthermore, the paper describes the current work of the authors, highlighting the scope of the Berlin Experimental and Educational Beacon (BEECON) project by Technische Universität Berlin (TU Berlin). Those activities are not designated to specific technologies but are currently aligned with open-source technical approaches by the Libre Space Foundation (LSF), working towards the in-orbit verification of a spread spectrum identification and Doppler tracking solution called Spacecraft Identification and Localization (SIDLOC). This collaborative work includes technical development, manufacturing, integration, and in-orbit testing, using rideshare on different missions. Finally, the work also includes an important aspect of regulatory and harmonisation work toward future interoperable frequency bands and interfaces.

Keywords: Operations; Satcom; Smallsats; Tracking Aids; SSA; STM; RSO; ESA; DLR; ITU.

1. BACKGROUND

The need for interoperable radiocommunication solutions for self-identification and tracking can be derived from the increasing number of smallsat-launches and the challenges for operators to track and identify their newly launched spacecraft. This is also known as the so-called "CubeSat confusion" within rideshare launches where it takes typically weeks to obtain first third-party orbital data for the new satellites. Tracking aids can facilitate the trackability and in some cases also the identification of space objects, having their specific advantages and drawbacks. This section gives a brief overview of the current smallsat (r)evolution, tracking, and identification methodologies, as well as a classification of the tracking aid principles.

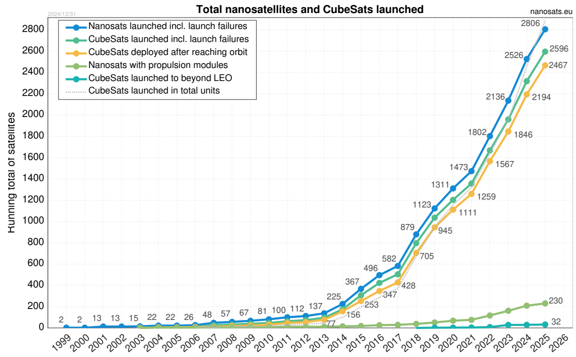

Figure 1. Smallsats launched to date. [1]

1.1. Smallsat (R)evolution

The current trend of newly launched small satellites below 500 kg, called smallsats, shows an exponentially increasing number of objects in space. Fig. 1 shows the total number of nanosatellites and CubeSats launched until the end of 2024. There are different projections for the coming decade, starting with tens of thousands to millions of new satellites in Low Earth Orbit (LEO). Precise predictions are not possible today, but "even under the no further launches scenarios, the amount of space debris objects is observed to increase in all cases" [2] according to the European Space Agency's (ESA) Annual Space Environment Report.

Apart from the general Space Situational Awareness (SSA), including the number of objects and the knowledge about their according trajectories itself, the current Space Traffic Management (STM) is mainly stochastic via orbital lifetime for smallsats. Meaning: to date, lots of LEO satellites have been deployed into specific orbits, purely depending on their drag to re-enter Earth's atmosphere within a given timeframe. Managing collision avoidance manoeuvres is purely based on manual analysis of a specific situation and communication with multi-

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ple entities at the satellite operator level due to the lack of established procedures for automated STM. Furthermore, there are no interoperable tracking systems without the need to actively search for the spacecraft, which is left to the operators themselves.

1.2. Tracking and Identification

It takes two steps to achieve a space situational overview object by object. First, the spacecraft must be detected and tracked by orbit determination using either velocity or distance at multiple tracking points. For this purpose, there are several approaches with different advantages and drawbacks:

- Optical tracking, the earliest method, is used to check for reflections of sunlight. Depending on the size and surface of the spacecraft, telescopes are needed. Nano- and picosatellites are almost impossible to find from the ground.
- Laser ranging is an optical method as well but uses a ground-based laser source as a reference signal to be reflected by an object in space. The technology is very expensive, but results in a precise orbit determination within the resolution of centimetres. However, the search beam width is about 0.5 degrees and therefore is not suitable for the initial detection of newly launched spacecraft.
- Radar systems are very expensive to build and their operation is very resource-intensive as well. So far, this is the state-of-the-art technology for SSA depending on governmental actors sharing their data with the public.
- Electromagnetic emissions from spacecraft can be mapped to specific orbits either by analysing Doppler characteristics or by determining the direction of the radio or emitted light source. Because there is no standard emission to look for, this method needs to be customised for every single spacecraft and is only applicable to active missions in space.

Following the detection and orbit determination of objects in space, the identification of those is very challenging due to a limited set of methodologies:

- The characteristics of reflections can be analysed. Reflections in the radio frequency (RF) or visible spectrum, using the above optical, laser, or radar methods, can reveal surfaces or sizes of tracked objects.
- Radio transmissions are often the confirming method for identifying a specific spacecraft. The frequency, modulation, encoding, protocol, or even a particular RF signature can link an object trajectory to a known candidate. Those parameters are sometimes publicly shared and could be verified by frequency filings at the International Telecommunication Union (ITU). But from outside the operating entity it is difficult and sometimes impossible to be able to relate the actual object to a filed satellite system. Furthermore, analysis of radio transmissions is only possible within the range of one of the associated ground stations and depends on the operability of the spacecraft itself.
- The knowledge of the separation parameters, for example as state vectors, is offering a possibility for an estimation of the resulting orbit. This could even be reduced to a known sequence of separated spacecraft.

Combining all those methodologies described can lead to a clear picture of orbiting spacecraft, but requires a lot of system-specific knowledge and is always based on the combination of different indicators and evidence. Whatever the case may be, the identification is mainly based on manual processes which are difficult to automate. Therefore, identification takes days, months, or is never achieved due to missing information (see also ESA's statistics of identification rates for rideshare launches in [2], p. 35). Furthermore, even detection without any identification itself is limited by the tracking capabilities and capacities of radar systems.

The European Space Surveillance and Tracking (EU SST) initiative by the European Commission started in 2021, aiming to merge sensor data from all over Europe. This approach facilitates access to SSA data, but still leaves the same information gaps and questions raised above.

1.3. Tracking Aids

As the name implies, tracking aids offer possibilities to support the tracking of spacecraft and help tackle the challenges described before. In general, they can be categorised into optical support devices on the one hand and radiocommunication devices on the other, both using the electromagnetic spectrum in different ranges and divided into passive and active functionality. Figure 2 shows a breakdown overview of the general systematics of the tracking aids.

Optical systems are often used passively. High-albedo surfaces, corner cube reflectors (CCRs), and reflective foils are used to increase visibility for telescopes. An overall and bright reflection of the visible spectrum is typically undesirable because it counteracts the effort to obtain dark and quiet skies (DQS), which is needed especially for astronomy observations. This effect is also known due to recent discussions about big constellations and their reflecting solar cells, which can be seen by the unaided eye. Additionally, smallsats are typically too small for this approach. To increase their optical trackability, CCRs and reflective foils are used, mainly to sup-

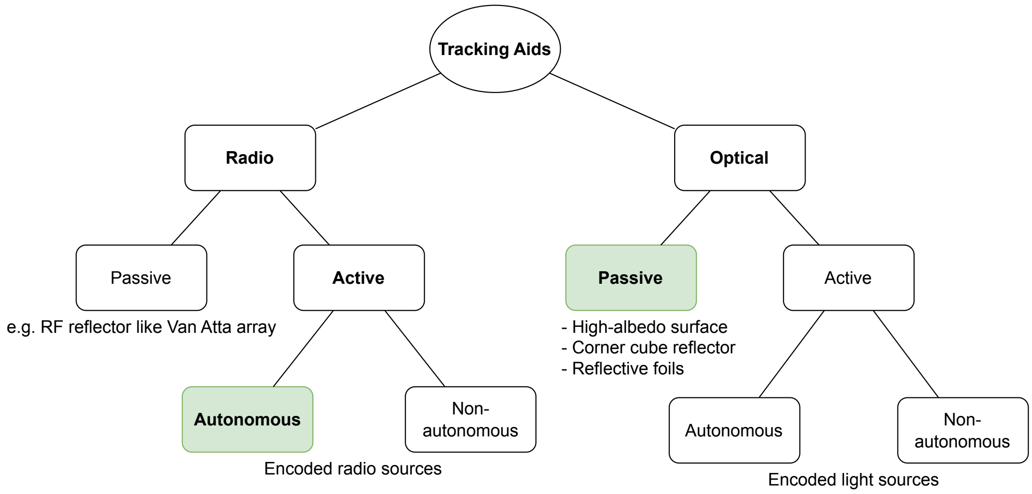

Figure 2. Systematisation of tracking aids.

port laser ranging systems. However, as described before, optical tracking is not suitable for initial detection of an object, even though high resolution can be achieved. Encoded light sources, working autonomously or non-autonomously, can facilitate identification via telescopes. Following the paradigm of DQS, there are no systems in view that could be suitable for a broad adoption.

Radiocommunication systems are used mainly actively. Passive radio tracking aids are known but rarely used, such as the RF reflecting Van Atta arrays. Those devices are frequency selective and increase the RF visibility of the spacecraft but do not support any encoded information and furthermore consume a lot of valuable surface of the satellite. Active encoded radio sources are capable of transmitting radiocommunication beacons to track and identify spacecraft. In an effort to achieve independence from the hosting spacecraft, which could be dead on arrival (DOA) in the worst-case scenario, this type of tracking aid would be most beneficial working autonomously.

Considering all those categories of tracking aids, a combination for rough orbit estimation and object identification using autonomous radio beacons, combined with a passive optical tracking aid for detailed orbit determination, might be a suitable combination.

2. MOTIVATION

Radiocommunication solutions could facilitate the need to close the gaps in radar systems. Automatic Dependent Surveillance–Broadcast (ADS-B) for the aviation sector and the Automatic Identification System (AIS), used for maritime traffic management, can be seen as operational but not technical role models. Despite the broad use of radars for airspace and sea, active beacons are vital for the aviation and maritime sectors.

In order to close the gaps in radar systems in the space sector, radiocommunication devices could mainly support:

- Trackability by passive orbit determination on the ground via Doppler analysis of a known frequency, as well as radio ranging if the space segment supports receiving and transmitting signals.
- Information about the spacecraft, such as a unique identifier, but also optionally including additional status information, etc.
- Scalability with regard to the ubiquitous reception of self-identifying spacecraft with no need to actively scan only subareas of the visible sky.

Apart from this described motivation, radiocommunication can offer a set of features available to operators, providing the operating entity with information, from the first contact with the satellite until its reentry. Although space agencies and well-established big companies have resources to handle this operational challenge, other operating entities such as small- and medium-sized businesses (SMBs), universities, or commercial newcomers are purely relying on external support. Optionally, emergency intervention could be simplified if an uplink is available. For example, a mission could be saved by having a redundant communication system accessing the host in case of any failure. Another optional add-on to be discussed would be a trigger for end-of-life (EOL) disposal as a last resort.

Last but not least, sustainability is an increasing topic for the use of the outer space environment. From an economic point of view, the sustainable use of planet Earth's orbital resources ensures the protection of human space assets. But the avoidance of space debris also supports national, European and international sustainability and safety goals, fostering the ecological idea extended to the outer space environment.

3. APPROACHES TO DATE

Several radiocommunication tracking aids have been proposed to date, shown in Table 1 for comparison. The systems mainly originate from the US and Europe, but also from Australia and India within the industrial or scientific research context. RILDOS differs from the other systems compared here, as it is not an actual implementation but specifications for a proposed standard only. Every other system comes in different shapes and sizes, meaning that there is no common understanding of a well-suited standard mechanical integration yet.

With respect to the RF link, different modulations and frequency bands are in use. The systems from the USA are using either the LEO (wideband) code-division multiple access (WCDMA) network, run by the US-based company Globalstar in the 1600 MHz band, or frequency-shift keying (FSK) in the 915 MHZ industrial, scientific, and medical radio (ISM) band for ITU Region 2 (Americas, Greenland, and some eastern Pacific Islands). ANT61 from Australia uses Quadrature phase-shift keying (QPSK), connecting to the Iridium network, provided by a US-based company in the 1600 MHz L-band as well. The European systems are focussing on two bands allocated to the space operation radiocommunication service (SOS), specifically the 137-138 MHz band and the 401-402 MHz band. Apart from the FSK-based OWL system, direct-sequence spread spectrum (DSSS) binary phase shift keying (BPSK) modulation, also abbreviated DS-BPSK, is implemented by SIDLOC and BEECON. Every modulation and frequency band in use has its benefits and drawbacks which need to be examined further in future work.

Lifetime is a very complex feature to identify. With respect to battery power, a system can be autonomous if it is capable of powering itself not depending on the hosting spacecraft and therefore having its own power subsystem. OWL is designed for initial acquisition of a CubeSat at the beginning of the launch and early orbit phase (LEOP), lasting for 18 hours while ANT61 lasts 1-3 weeks. CUBIT states a lifetime of 30 days, probably supporting a whole LEOP. Because this is the crucial phase of satellite commissioning, these systems could be beneficial to smallsat operators. The *Proof of Life* beacon from CIPHOR relies on the batteries of the hosting satellite bus. All other systems are supposed to work autonomously, independently from the spacecraft, but they are not specifying which lifetimes are expected.

Finally, licencing seems to be an important issue for broad adoption. Like the technical characteristics, they would need to be examined further. For commercial purposes, some companies have chosen a proprietary approach to protect their investment in development. Other developers are using open licences to support the acceptance, reproduction, and adoption of other entities.

It can be stated that there is no broad exploitation of any system yet. All of the systems mentioned are either not applicable in their current design or did not find broad adoption within the (small) satellite community.

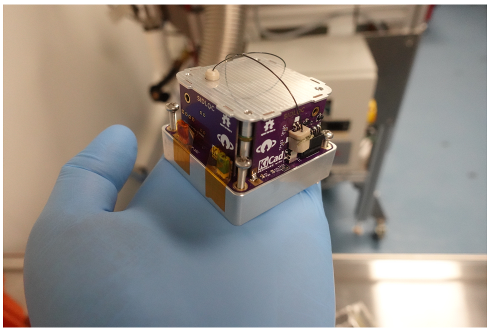

Figure 3. Assembled flight model for SIDLOC-AR6 experiment. (Credit: LSF)

4. SIDLOC

Spacecraft Identification and Localization (SIDLOC) is a proposed system by the Libre Space Foundation (LSF), adopting elements of the formerly proposed Radio with Identity and Location Data for Operations and SSA (RILDOS) [3] standard. The LSF has published a manifesto with five principles and four pillars, including open knowledge. Furthermore, they are involved in multiple ESA, and free and open-source software (FOSS) community projects with the Satellite Networked Open Ground Station (SatNOGS) as their most known project.

The SIDLOC scope comprises mainly the identification and tracking via Doppler shift measurements based on RILDOS. It is proposed to co-exist with other space operations within the same frequency range aiming at 401-402 MHz SOS usage.

4.1. SIDLOC-AR6 Experiment

The LSF successfully demonstrated the DSSS principle as a hosted payload on the Ariane 6 maiden flight. A PocketQube-shaped (5x5x5 cm^3) demonstrator (Fig. 3) was bolted to the upper stage sharing the ride with multiple other experiments. Since the upper stage of Ariane 6 was supposed to re-enter the atmosphere of Earth, the experiment was planned as a battery-powered proof of concept. However, the short run-time was sufficient for a successful verification of the DSSS transmission.

Figure 4 shows a plot of the received DSSS signal from SIDLOC-AR6. On the X-axis the number of decimated samples is plotted from sample 0 to 36000. The pattern used was 30 seconds of transmission and 20 seconds of pause between transmission bursts. On the Y-axis the plot depicts the estimated Doppler frequency offset between positive and negative 11 kHz, centred at 0 Hz. Every Gold sequence of 2047 bits was repeated 20 times per

Table 1. Overview comparing different radiocommunication tracking aids to date.

System	Developer	Origin	Shape	Modulation	Freq. Band	Lifetime	License
ANT61 B.	ANT61	AUS	Four versions	QPSK	1600 MHz	1-3 weeks	propr.
BEECON	TU Berlin	D	Patch	tbd.	tbd.	autonomous	open
Black Box	NSL	USA	Three versions	(W)CDMA	1600 MHz	autonomous	propr.
Blinker	Aerospace	USA	Side Panel Box	FSK?	915 MHz	autonomous	propr.
CUBIT	SRI	USA	Elec.+Ant. Unit	FSK?	915 MHz	30 days	propr.
OWL	C3S	ESA/HNG	Tuna Can	FSK?	137 MHz	18 hours	propr.
Proof of L.	CIPHOR	IND	Patch?	*unknown*	UHF/70cm	bus power	propr.
RILDOS	Kratos et al.	USA	*Specs only*	DS-BPSK	*TM Inband*	none	open
SIDLOC	LSF/FORTH	ESA/GRC	PocketQube	DS-BPSK	401 MHz	autonomous	open

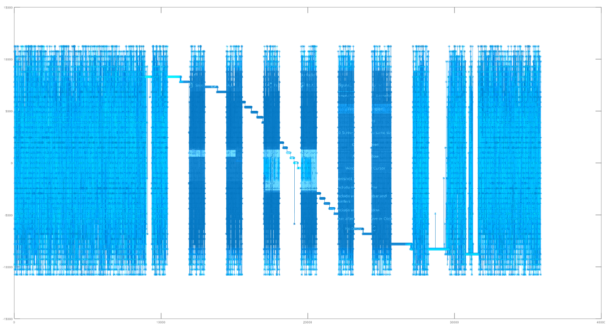

Figure 4. Received DSSS signal showing the Doppler curve. (Credit: LSF)

spread symbol. The result of the experimental proof of concept shows a clear Doppler curve to be further processed for orbit determination.

5. BEECON

The Berlin Experimental and Educational Beacon (BEECON) is funded by the German Aerospace Center (German: Deutsches Zentrum für Luft- und Raumfahrt, DLR) with the objective to seek German and European cooperation towards international solutions. For the scope of the project, four main challenges were identified:

1. Technical development with the view towards miniaturisation, energy efficiency, low-cost production, fail-safe operation, and simple integration into a hosting spacecraft.

2. Regulatory frameworks at the national, European, and international levels. The application within one or multiple specific frequency bands of an identified radiocommunication service is crucial for the future use of radio tracking aids.

3. Even if it is too early for harmonisation or standardisation, it is important to have those related questions in mind, like, for example, the possible standardisation bodies.

4. Finally, a significant contribution for SSA is the adoption by individual satellite operators. The features of any proposed system need to match their needs.

The BEECON project follows the vision of a simple plug-and-play attachment to any spacecraft. Furthermore, no expensive and time-consuming frequency coordination (CN) or seeking agreement (AN) shall be needed for using such a device, in order to lower the barriers for (small) satellite operators.

5.1. Technical Overview

To gain knowledge and experience without starting from scratch, the basic design goals and technical parameters of SIDLOC were adopted to transmit a unique satellite identifier (ID), optionally: the location and the status of the satellite. The whole system must not exceed an average power budget of 40 mW. DS-BPSK modulation is used with an RF peak power of 400 mW at 900 kHz bandwidth, leading to an RF power density smaller than -33 dBm/Hz.

With the additional purpose of hardening the system, the design was adapted to a discrete transmitter architecture. This allows for higher durability, lower power consumption, and vendor independence, compared to a design based on software-defined radios (SDR) and field-programmable gate arrays (FPGA). It comes with the cost of adaptability, but the decision was taken on the basis of the objective of creating a beacon system that could outlive the host spacecraft. To have the final experimental device available by 2026, the overall design goals should also meet the following: autonomous power system, self-contained within 50x50x6 mm^3, and transmitting a unique beacon for identification and tracking.

The preliminary design of the BEECON can be seen in Fig. 5. A printed circuit board (PCB) mounted outside is dedicated for power purposes: It incorporates an electrical power system (EPS), a solar panel for energy harvesting, and an energy storage that is not yet defined. Energy could be stored in contained lithium batteries, capacitors, or solid-state batteries (SSB). Because it needs to be faced outward, a retro reflector or retro foil complements the power PCB. The heart of the identification PCB is the microcontroller unit that offers an optional periphery interface to the host satellite. Furthermore, the microcontroller unit (MCU) controls the deployment mechanism of the antenna and the RF chain. For beacon capabilities a discrete DS-BPSK transmitter is used which connects to the RF front end (RFE), and finally to the antenna for RF transmission within the 401-402 MHz band. This band is purely experimental for technical studies and does not infer any regulatory designation. In a band not defined yet, an optional uplink can be implemented to control the MCU for performing experiments or interfacing with the satellite.

5.2. Regulatory Overview

The ITU Radio Regulations define rules concerning transnational radio frequency usage under international law, accepted by 194 member states. The table of frequency allocations in article 5 assigns RF bands to radiocommunication services and defines their respective usage constraints. Since the edition of 1959, the first space services (SPACE) have been allocated to regulate the usage of radiocommunication between Earth and space. Not even 10 years later, in 1968, satellite identification was added to the SPACE frequency allocations in the range 30.005-30.010 MHz, named space operation service (SOS) since 1971. Between then and now space communication is gaining in relevance, regulated by multiple services in frequency bands all over the RF spectrum.

Following the "ITU-R's contribution in implementing the outcomes of the World Summit on the Information Society and the 2030 Agenda for Sustainable Development" (Res. 61-2, Radio Assembly 2019) and "ITU's role in the implementation of the "Space2030" Agenda" (Res. 218 and 219, Plenipotentiary Conference 2022), the resolution ITU-R 74 "Activities related to the sustainable use of radio-frequency spectrum and associated satellite-orbit resources used by space services" was adopted by the Radio Assembly 2023. A proposed Study Question (SQ) by Germany with "Studies related to possible radiocommunication solutions for the identification and tracking of spacecraft [and debris]" in 2023 was an approach to find a common understanding of a future regulatory roadmap. On the one hand, within the Study Group (SG) 7, the Working Party (WP) 7B, which has the SOS under purview, so far no consensus on possible technical activities could be reached. On the other hand, SG 4, WP 4A is directly tasked with ITU-R 74, in particular writing a "Handbook on best practices for the sustainable use of frequencies and associated non-GSO orbits by space radiocommunication services" as well as a "Handbook on Satellite Communications and Technologies" also describing space debris mitigation mechanisms.

Due to ongoing discussions regarding possible overlaps of the mandates between the United Nations Office for Outer Space Affairs (UNOOSA), supporting the Committee on the Peaceful Uses of Outer Space (COPUOS) on one side and the ITU on the other, it is currently challenging to tie technical discussions on the overall issue of space sustainability, lacking clear definition and distinction.

6. SIDLOC-BEECON: MISSION OVERVIEW

LSF and TU Berlin agreed to perform multiple experimental in-orbit demonstrations (IOD), based on a joint ITU frequency filing as well as mutual information exchange and knowledge transfer. While LSF continues their SIDLOC development funded by ESA and launched with Ariane 6 (see section 4.1), TU Berlin used a last minute opportunity to adapt, build, and test this first design as part of the InnoCubE mission. This SIDLOC-BEECON experiment can be seen in Fig. 6 before integration into InnoCubE: the approx. 90x45x10 mm^3 amateur radio payload PCB holds the DS-BPSK beacon transmitter on the top right, as well as the RF front end (RFE/RFFE) on the top left.

Multiple other experimental missions are scheduled between 2024 and 2026 according to Tab. 2. Unlike the proof-of-concept mission fixed to the 2^{nd} stage of Ariane 6, the Erminaz and UARX missions run by LSF aim to be standalone PocketQubes having their autonomous EPS and to be launched in June 2025. TU Berlin's upcoming milestone is focused towards an IOD of their discrete DSSS transmitter and antenna deployment mechanism, with lower prioritisation on the Power PCB (see section 5.1). This experiment is planned for the A4/NEO-1 mission of the National Research and Innovation Agency (Indonesian: Badan Riset dan Inovasi Nasional, BRIN), formerly developed by the dissolved National Institute of Aeronautics and Space (Indonesian: Lembaga Penerbangan dan Antariksa Nasional, LAPAN). Finally, the QUEEN mission from TU Berlin is supposed to host the final demonstrator experiment integrating the full BEECON system design.

7. SUMMARY AND OUTLOOK

Regarding radiocommunication approaches towards interoperable autonomous self-identification and tracking, there are first approaches and flight experiments to be noted. Unfortunately, so far, all companies and communities seem to be distinct from each other. LSF and TU Berlin are working to build awareness and knowledge within the communications, operations, and space debris

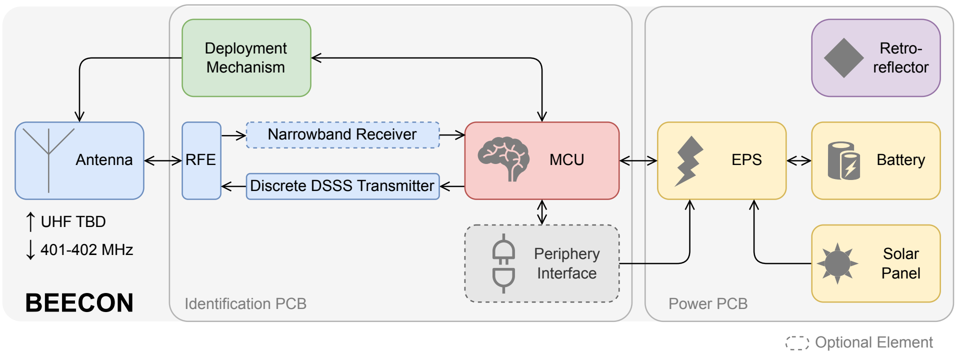

Figure 5. Block diagram of the BEECON design.

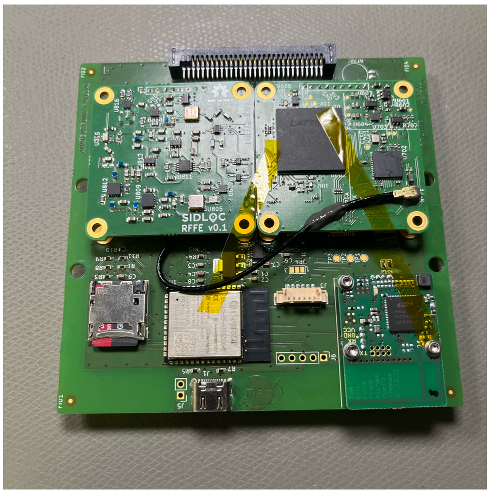

Figure 6. Integrated BEECON-SIDLOC payload for the InnoCubE mission.

Table 2. SIDLOC-BEECON mission schedule, planned for 2024-2026.

Mission	Ops	Launch	Spacecraft
Ariane 6	LSF	2024-07-09	2nd Stage
InnoCubE	TUB	2025-01-14	3U CubeSat
Erminaz	LSF	2025/06	PocketQube
UARX	LSF	2025/06	PocketQube
A4/NEO-1	TUB	2026/Q1	150 kg Sat
QUEEN	TUB	2026/Q4	64U "Cube"

communities. Starting on a European level, only international cooperation and simplified legal processes with regard to licences and spectrum usage can lead to broad acceptance and exploitation. Nevertheless, this topic of overall spacecraft identification and tracking is at the very beginning of it's evolution with a strong need from satellite operators to handle the "CubeSat confusion" during rideshare launches and mass deployments.

To facilitate this evolution, more technical development, experiments, and public results are needed. Even more important than actual applications or products is the sharing of ideas towards technical harmonisation, related to frequency bands, modulation techniques, and protocols with a future standardisation in view. Frequency bands that are not subject to coordination or seeking agreement are mandatory. The usage of open standards for modulation and the following upper layers is the most promising path, making it easier to collaborate and contribute at the European and global level.

ACKNOWLEDGEMENTS

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