# SIDLOC: Spacecraft Identification and Localization

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***Abstract*—SIDLOC (Spacecraft Identification and Localization) is a new transmission scheme proposed by Libre Space Foundation, in collaboration with ESA, SIDLOC aims to improve space safety and mission success rate by establishing an open beaconing standard for spacecraft identification and localization. The system relies on a reduced size autonomous transmitter that requires minimal integration and area on the carrier spacecraft. The ground segment of the SIDLOC system utilizes the existing SatNOGS network and the UHF band to perform the signal demodulation and identification. The SIDLOC system uses DSSS (Direct Sequence Spread Spectrum) PSK modulated signals with an effective bitrate of 50 bits/s. The use of DSSS is crucial in order to achieve reliable reception with the minimum possible transmission power. Through an accurate Doppler frequency shift estimation mechanism, the SIDLOC system provides orbit determination capabilities, enabling open and independent SSA (Space Situational Awareness) activities.**

**SIDLOC has already deployed in space on-board the second stage of Ariane-6 and successfully retrieved the trajectory of the rocket body, from the first pass over a ground station in North Europe. The next expected mission is on Transporter-14 with 3 different beaconing PocketQube sized spacecrafts.**

## I. Introduction

The exponential increase in orbital objects, driven by the proliferation of small satellite constellations and diverse mission architectures, has outpaced the capabilities of existing Space Situational Awareness (SSA) and Space Traffic Management (STM) systems. Traditional tracking methods, such as radar and optical observations, are limited in their ability to detect and monitor objects smaller than 10 cm in diameter. Furthermore, public orbital data sources often lack transparency and timeliness, with Two-Line Element sets (TLEs) becoming obsolete within hours to days post-launch, particularly during the critical Launch and Early Orbit Phase (LEOP).

The deployment of large numbers of small satellites, such as CubeSats and PocketQubes, into similar orbital planes exacerbates the challenge of individual object identification and tracking. This scenario complicates collision avoidance strategies and increases the risk of untracked debris, posing significant threats to operational spacecraft and the sustainability of space activities[1].

Accurate and timely identification and localization of spacecraft are imperative for ensuring the safety and success of satellite operations. Disruptions caused by RF collisions or misidentification can have cascading effects on critical infrastructure, national security, and economic activities reliant on space-based services. Therefore, enhancing SSA capabilities to include reliable tracking and identification of all space objects, regardless of size, is essential.

In response to these challenges, the Spacecraft Identification and Localization (SIDLOC) system has been developed as an open-source solution to provide standardized, autonomous identification and localization of spacecraft. SIDLOC employs a compact, low-power beacon transmitting Direct Sequence Spread Spectrum (DSSS) signals, enabling precise orbit determination through Doppler shift analysis. By integrating with the global SatNOGS[2] network of ground stations, SIDLOC facilitates real-time tracking and identification, thereby enhancing SSA and contributing to safer and more sustainable space operations.

## II. The SIDLOC System

The SIDLOC system is designed to provide autonomous, low-power, and cost-effective identification and localization of spacecraft, particularly during the critical Launch and LEOP and post-mission disposal periods. Developed by the Libre Space Foundation (LSF) in collaboration with the European Space Agency (ESA), SIDLOC offers a standardized approach to enhance SSA and STM capabilities.

The key features of the system are:

- **Low Power Consumption**: SIDLOC employs DSSS with Binary Phase Shift Keying (BPSK) modulation, achieving reliable signal reception at an effective bitrate of approximately 50 bits per second. The computational requirements of the transmitter are kept minimal and can be easily fulfilled by Complex Programmable Logic Devices (CPLDs) or low end Field-Programmable Gate Arrays (FPGAs). In addition, the low TX power requirements are also minimal, requiring $\approx 25$ dBm for typical Low Earth Orbit (LEO) missions.
- **Cost-Effective and Maintenance-Free**: The system's simplicity and reliance on existing infrastructure, such as the SatNOGS network, reduce both implementation and operational costs. Its autonomous nature eliminates the need for ongoing maintenance, making it suitable for long-duration missions and post-mission tracking.
- **Minimal Integration Effort**: SIDLOC's compact form factor adaptability and lack of special requirements enable seamless integration into various spacecraft platforms, including CubeSats and PocketQubes (Figure 1). The design allows for straightforward incorporation without significant modifications to existing systems.
- **Autonomous Operation**: Once deployed, SIDLOC operates independently, transmitting identification beacons without the need for external commands or intervention.

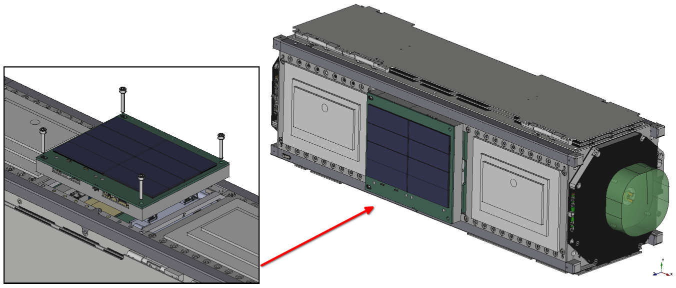

Fig. 1. SIDLOC integration into a 3U Cubesat

This autonomy ensures continuous tracking capabilities, even in scenarios where the primary spacecraft systems are inactive or compromised.

- **Dedicated Frequency Band**: Operating within the 401–402 MHz frequency range, SIDLOC utilizes a 1 MHz bandwidth to transmit its signals. This allocation minimizes interference with other communication systems and complies with international frequency regulations.
- **Integration with Existing Ground Station Networks**: SIDLOC leverages the global SatNOGS network, an open-source collection of satellite ground stations, for signal reception and processing. This integration facilitates widespread adoption and enhances the system's scalability.
- **Rapid Identification and Localization**: Through the analysis of Doppler frequency shifts in received signals, SIDLOC enables precise orbit determination and swift identification of spacecraft. This capability is crucial for maintaining accurate orbital catalogs and ensuring timely responses to potential collision threats.
- **Scalability for Large Constellations**: The system's design supports the simultaneous tracking of thousands of satellites, addressing the growing need for effective management of large satellite constellations and reducing the risk of orbital congestion.
- **Support for LEOP and Post-Mission Disposal**: SIDLOC's autonomous and continuous operation provides critical support during the LEOP, when traditional tracking methods may be limited. Additionally, it aids in monitoring spacecraft during post-mission disposal phases, contributing to responsible space debris management.
- **Open on every aspect:** Unrestricted access, independent validation, data sharing and collaboration are key requirements for SSA and STM[3]. Towards this, SIDLOC is a complete open system. The specification, the reference hardware as well as the software and the resulting data are released as open-source and open-hardware.

### *A. SIDLOC Framing Schemes*

SIDLOC defines three distinct beacon framing schemes to support a range of operational scenarios and system constraints:

- **Minimal Frame:** Contains only the essential fields necessary for satellite identification and coarse localization, including the SIDLOC protocol identifier and a unique satellite identifier. The reduced frame size allows for extremely short transmission durations, making it particularly suitable for satellites with limited power budgets or during critical low-battery conditions.
- **Full Frame:** Extends the minimal frame by incorporating time and positional information, typically acquired from an onboard GNSS receiver. This enables higher localization accuracy through fusion with ground-based Doppler shift observations.
- **Integrated Frame:** Provides maximum flexibility for integrators by allowing customizable data field selection. This frame can optionally piggyback telemetry from the host spacecraft, enabling operators to monitor key mission parameters, especially during LEOP, such as antenna deployment status or basic health indicators. The three different frame types and their differences are summarized in Table I. Detailed information regarding the fields of the SIDLOC beacon can be found at Table II.

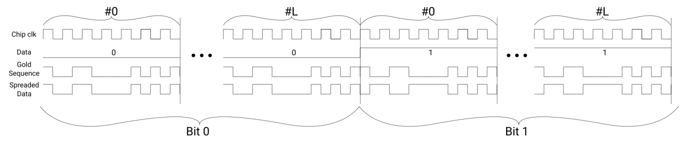


Fig. 2. DSSS spreading procedure

### *B. Modulation and Coding*

SIDLOC employs DSSS modulation technique to enhance resilience against interference, enable low-power transmissions, and support multiple concurrent, unmanaged transmissions. This approach is particularly suited for the challenges of space communication, where signal integrity and power efficiency are paramount. At the symbol level, SIDLOC utilizes BPSK modulation. BPSK is chosen for its robustness and simplicity, making it effective for low-power transmissions in the presence of noise and interference.

The DSSS spreading (Figure 2) is achieved using a Gold[4] sequence. Gold sequences are preferred in spread spectrum systems due to their favorable cross-correlation properties, which are essential for distinguishing between multiple signals in a shared frequency band. The period of the Gold sequence in SIDLOC is 2047 bits. This length represents a balance between achieving sufficient processing gain and maintaining manageable computational complexity for demodulation and decoding processes at the ground station.

To align with the target chip rate of 1 Megachip per second (MCPS), each data bit is represented by repeating the 2047-bit Gold sequence ten times. This repetition results in a total of 20,470 chips per data bit. Consequently, the effective data rate ($R$) is calculated as follows:

$$
\begin{aligned}
R &= \frac{\text{Chip Rate}}{\text{Gold Sequence Length} \times \text{Repetitions}} \\
&= \frac{1 \times 10^6}{2047 \times 10} \approx 48.9\,\text{bps}
\end{aligned} \tag{1}
$$

TABLE I
SIDLOC BEACON TYPES

| Data Type | Minimal | Full | Integrated |
|---|---|---|---|
| SIDLOC Identification Info | Required | Required | Required |
| Unique Satellite Identifier | Required | Required | Required |
| Timestamp (Date/Time) | Not Included | Required | Optional |
| Position Information | Not Included | Required | Optional |
| Satellite Status | Not Included | Not Included | Optional |
| Reserved Data Fields | Not Included | Not Included | Optional |

TABLE II
SIDLOC BEACON FRAME STRUCTURE

| # | Field Name | Size (bits) | Size (bytes) | Description |
|---|---|---|---|---|
| 0 | Sync Word | 24 | 3 | Frame synchronization sequence (0xFFF) |
| 1 | SIDLOC Type | 4 | 0.5 | Identifier for SIDLOC type and version (16 values) |
| 2 | Satellite ID | 72 | 9 | Unique satellite identifier (UUID) |
| 3 | TJD | 16 | 2 | Truncated Julian Date |
| 4 | Seconds of Day | 16 | 2 | Elapsed seconds since midnight UTC |
| 5 | Coordinate System | 2 | 0.25 | 00: Geocentric, 01: HEEQ |
| 6 | Position X | 28 | 3.5 | Range: ±134,217,728 meters |
| 7 | Position Y | 28 | 3.5 | Range: ±134,217,728 meters |
| 8 | Position Z | 28 | 3.5 | Range: ±134,217,728 meters |
| 9 | Velocity X | 24 | 3 | Range: ±10,485.75 m/s |
| 10 | Velocity Y | 24 | 3 | Range: ±10,485.75 m/s |
| 11 | Velocity Z | 24 | 3 | Range: ±10,485.75 m/s |
| 12 | Acceleration X | 18 | 2.25 | Range: ±655.35 m/s² |
| 13 | Acceleration Y | 18 | 2.25 | Range: ±655.35 m/s² |
| 14 | Acceleration Z | 18 | 2.25 | Range: ±655.35 m/s² |
| 15 | Satellite Status | 8 | 1 | Operational status flags |
| 16 | Satellite Usage Info | 8 | 1 | Application-specific metadata |
| 17 | CRC | 8 | 1 | Frame integrity check (Cyclic Redundancy Check) |
| **–** | **Total** | **368** | **46** | |

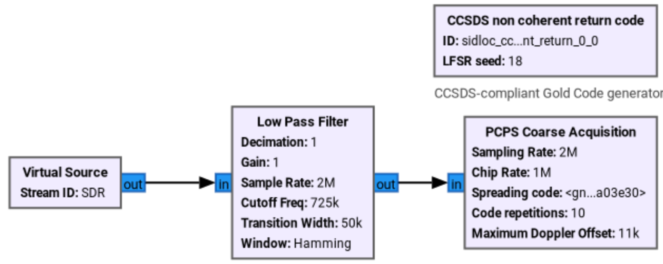


Fig. 3. GNU Radio flowgraph for SIDLOC reception

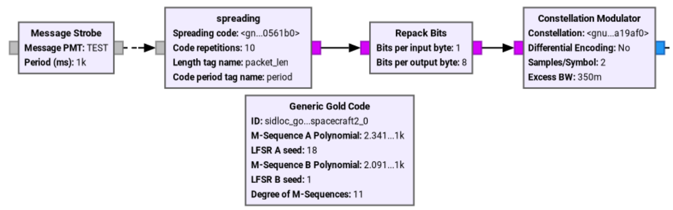


Fig. 4. SIDLOC transmission example flowgraph

### C. Demodulation and Frequency offset estimation

For the decoding and the frequency offset estimation a method known as Parallel Code Phase Search (PCPS)[5] is used, a well established algorithm from the GNSS systems, which shares a lot of similarities with the SIDLOC system. This algorithm, instead of the computationally heave convolution, required by the cross-correlation de-facto DSSS decoding method, uses FFT and IFFT to retrieve both the symbol phase as well as the frequency offset. Utilizing the repetitions of the same Gold sequence, non-coherent integration improves the system performance by averaging the results of each symbol multiple times.

The whole demodulation and frequency extraction process is implemented in *gr-sidloc*[6], a GNU Radio Out-of-Tree (OOT) module. This module provides not only the processing blocks for reception (Figure 3) but flowgraphs and processing blocks for transmission too (Figure 4), allowing for further experimentation and easier adoption of the protocol.

### D. Localization process

To derive position estimates, the SIDLOC system performs Doppler-based localization by fitting observed frequency offsets from ground station receivers to expected orbital trajectories. This curve fitting process is implemented in the STRF toolbox [7]. When used in conjunction with a dense, globally distributed network such as SatNOGS, multiple independent frequency offset measurements can be aggregated to substantially enhance localization accuracy.

Beyond identifying matches to known orbital elements, the SIDLOC system together with STRF tools also support trajectory refinement. They can generate updated TLEs or even propose entirely new orbital solutions that best align with the observed Doppler profile. These capabilities are particularly

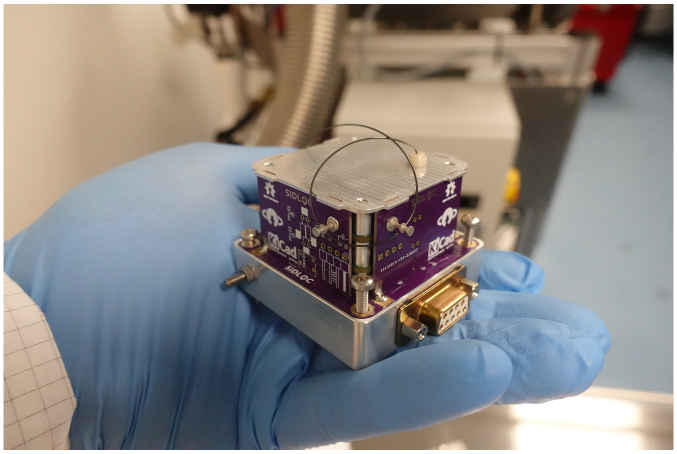

Fig. 5. Ariane 6 SIDLOC beacon

valuable during LEOP, when initial TLEs provided by launch providers may contain substantial uncertainties. Moreover, in large-scale deployments, small variations in deployment timing can result in non-negligible divergence between individual satellite trajectories, further underscoring the importance of such refinement tools.

## III. In-Flight Demonstration on Ariane 6

The SIDLOC system underwent its first in-flight demonstration during the maiden flight of the Ariane 6 launch vehicle, designated VA262, on 9 July 2024. SIDLOC was integrated as a hosted payload on the Ariane 6 upper stage (Figure 6), remaining attached throughout the mission to facilitate continuous tracking and identification.

The upper stage was designed to perform two orbital passes before a planned deorbit over the Indian Ocean. However, due to a malfunction in the Auxiliary Propulsion Unit (APU), the final deorbit burn was not executed, resulting in the upper stage remaining in a 580 km circular orbit. Unfortunately, due to the initial two orbital passes plan, SIDLOC beacon was not equipped with solar panels and the battery was designed to last few hours.

For the purpose of the Ariane 6 experiment, a custom hardware stackup was selected shown in Figure 5. This configuration follows the PocketQube specification, with some extra requirements dictated by the launch provider. The beacon was powered autonomously by its own battery pack. The antenna deployment sequence was instructed from the rocket flight computer through the D-Sub9 connector. Note that the D-Sub9 connector is huge comparing to the rest of the beacon, but this was also mandated by the launch provider.

To evaluate SIDLOC performance, three dedicated SatNOGS ground stations equipped with Ettus Research B200mini[8] Software Defined Radio (SDR) and a 10 MHz GPS Disciplined Oscillator (GPSDO) were deployed. The purpose of this station was to capture the raw signal during the pass of the Ariane 6 upper stage. Later, the raw signal files were fetched for post-processing and offline analysis.

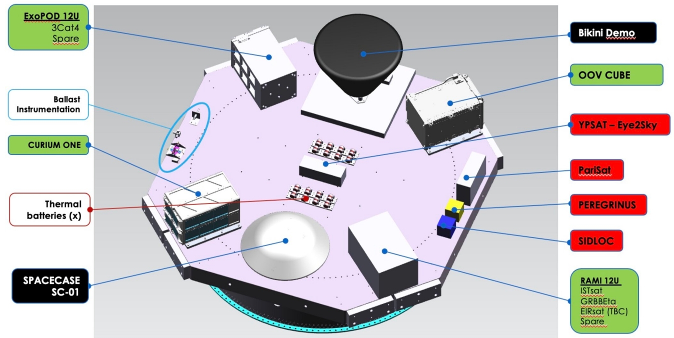


Fig. 6. SIDLOC placement on Ariane 6 upper stage

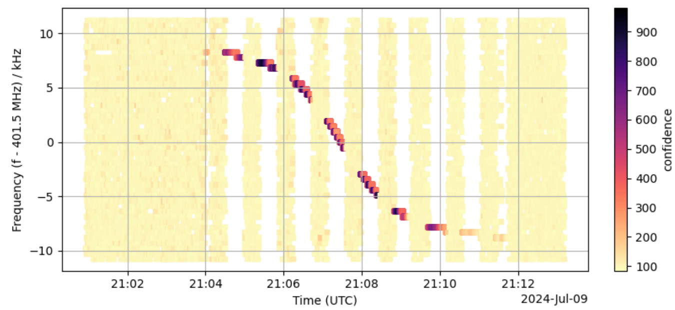


Fig. 7. SIDLOC frequency estimation during the first pass over Sweden

During the Ariane 6 demonstration, the SIDLOC beacon did not transmit a standard frame with populated protocol fields. Instead, the frame contents were intentionally configured with an all-zero bitstream. This design choice eliminated any symbol transitions or ambiguity. In addition, the beacon was continuously transmitting the all-zero bitstream for 30 seconds, followed by 20 seconds pause, until the battery was depleted. This configuration made possible further experimentation with varying repetition factors of the Gold sequence, allowing characterization of system performance and link reliability within the constrained operational window of the Ariane 6 upper stage.

Figure 7 presents the frequency offset estimations derived from the signal captured during the first pass of Ariane 6 over a ground station located in Sweden. In addition to frequency offset values, the SIDLOC Doppler estimation algorithm computes a confidence level for each individual measurement. This confidence metric enables the filtering of unreliable or noise-corrupted estimates and it is depicted as a heatmap in the same figure.

The effect of applying filtering based on the confidence level is illustrated in Figure 8, where the resulting data clearly reveal the expected Doppler shift as well as the beaconing intervals specific to this experimental configuration. Together with the SIDLOC estimations, this figure also overlays the expected frequency offset based on the closest to the launch date TLE provided.

To perform localization for the experiment, the frequency offset dataset was converted into the format required by the

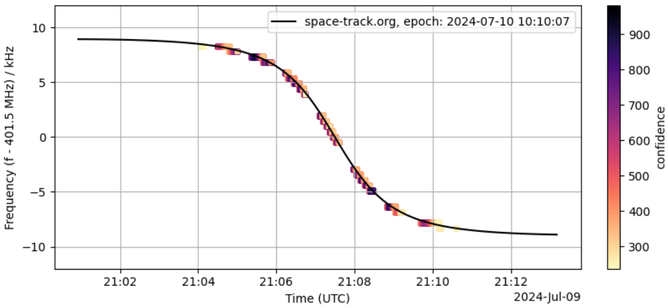


Fig. 8. Filtered estimations of Figure 7

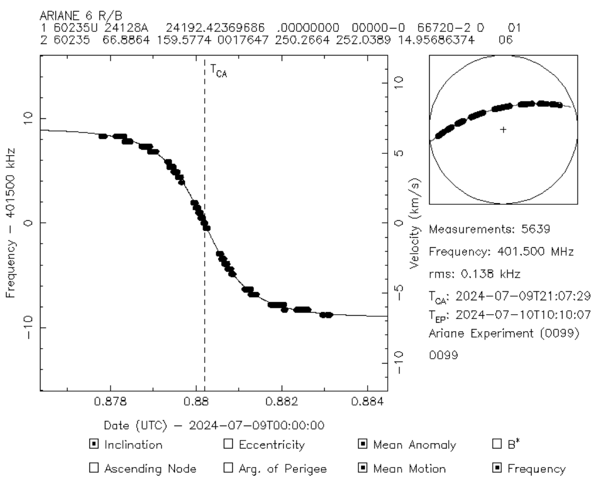


Fig. 9. STRF result based on the given frequncey offset estimations

*rffit* tool from the STRF toolbox. To mitigate the risk of local minima in the curve fitting process, the entire Space-Track TLE catalog [9] was supplied as input. The Ariane 6 TLE was manually replaced with the most accurate closest to the launch date.

Figure 9 shows the result of the matching process, where *rffit* correctly identified the Ariane 6 upper stage. The reported RMS residual of 0.138 kHz is consistent with expectations, given the use of the coarse frequency estimation algorithm, which provides a resolution of 488Hz. Future development is expected to narrow-down even more this ambiguity to few Hz.

Despite this coarse resolution, the experiment successfully demonstrated the SIDLOC system potential for accurate passive localization using open and low-cost infrastructure.

## IV. Conclusion

SIDLOC introduces an open, low-cost, and scalable solution for satellite identification and localization through Doppler-based passive tracking. By leveraging direct-sequence spread spectrum modulation and integration with globally distributed ground station networks such as SatNOGS, SIDLOC enables rapid, autonomous identification and orbit estimation, even for small satellites and debris-class objects.

The Ariane 6 demonstration validated the end-to-end viability of the system under real mission conditions, showing its ability to provide reliable Doppler measurements and support localization using existing open-source tooling like STRF.

As the orbital environment becomes increasingly congested, SIDLOC represents a significant step forward in enabling timely and resilient space situational awareness supporting both operational needs such as LEOP and long-term sustainability through post-mission tracking.

SIDLOC is currently under active development. Upcoming milestones include the integration of a fine frequency offset estimation algorithm to improve localization precision, as well as the implementation of a high-depth convolutional interleaver to enhance resilience against signal degradation caused by satellite tumbling. These advancements aim to increase robustness and further reduce reliance on external tracking data.

The entire development process, along with source code, hardware designs, and documentation, is publicly available at: https://gitlab.com/librespacefoundation/sidloc

## Acknowledgment

The authors would like to express their gratitude to the members of the SatNOGS community who contributed to the tracking efforts during the Ariane 6 mission. Special thanks also to the ground station operators who provided raw signal captures during the two scheduled passes of the rocket's upper stage.

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