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SRI International's CubeSat Identification Tag (CUBIT): System Architecture and Test Results from Two On-Orbit Demonstrations

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ABSTRACT

SRI International (SRI) developed the CubeSat Identification Tag (CUBIT) radio frequency (RF) transponder to demonstrate a low-SWaP (size, weight, and power) CubeSat RF-based identification system. CUBIT addresses the growing need to identify CubeSats post deployment as mass launches become more commonplace. Such launches make it difficult to assess which radar return belongs to which CubeSat, especially with the high mortality rates seen within the CubeSat community. Conversations with developers highlighted the need for better satellite identification for improved troubleshooting. Even for functioning CubeSats, the lack of accurate two-line elements (TLEs) increased the likelihood that ground assets were improperly aimed at the correct satellite. CUBIT seeks to address this need through a low-cost RF transponder.

This paper outlines the CUBIT system architecture. SRI's tag concept is composed of: (1) an internal Electronics Unit (EU) containing batteries, radio, and microprocessor and (2) an Antenna Unit (AU) containing the antenna and an inhibit photocell mounted on the CubeSat exterior.

SRI successfully demonstrated the CUBIT system during two On-Orbit operations. SRI teamed with NASA Ames for CUBIT's first demonstration using a collocated beacon and time domain signal analysis to confirm operation. In the second demonstration, CUBIT identified a passive CubeSat during a clustered launch and confirmed its deployment when other means provided ambiguous results.

INTRODUCTION

The SRI-developed CubeSat Identification Tag, or CUBIT (Figure 1), addresses what we perceive to be a growing need for identifying CubeSats after deployment independent of main SmallSat operation. This solution can also be used to identify other space objects, acting as a buoy of sorts, to help identify and track objects in space.

Figure 1: CUBIT addresses pressing needs within the CubeSat community.

A Pressing Need

Two primary developments within the space community, primarily associated with CubeSats, have prompted the need for CUBIT:

<u>CubeSat proliferation:</u> Cubesats and small satellites are growing in satellite market share due to lower launch costs (hundreds of thousands instead of tens of millions of dollars) coupled with increased launch availability (new launch vehicles focusing on small satellites supplement existing rideshare opportunities). In addition, new space architectures based on CubeSat constellations are in devevelopment.[1]

<u>CubeSat reliability:</u> CubeSat developments typically have smaller budgets and more compressed timelines. This is coupled with increased use of commercial off-the-shelf (COTS) components, decreased testing, and increased risk tolerance, resulting in a dead-on-arrival (DOA) rate exceeding 18%, with fewer than 60% still operating after 2 years.[2,3]

In general, CubeSats are deployed in large clusters from either dedicated or rideshare opportunities. Initial identification of individual satellites is difficult, and satellite name attribution must wait until distinct radar returns are correlated with other means of identification, usually a beacon of some sort. Issues arise when beacons fail, preventing unique identification, and when passive CubeSats are present. Misidentification or lack of identification prevents ground stations from tracking the appropriate satellite and impedes communication.

SYSTEM DESIGN & ARCHITECTURE

Design Drivers

Based on conversations with CubeSat developers, SRI developed a list of design drivers to inform the design.

<u>Low on-orbit SWAP:</u> Most CubeSats are volume constrained, with minimal space for additional systems. As such, CUBIT will need to be quite small to easily integrate within the main satellite structure and reduce system impact. If CUBIT requires ¼ of a U, then we believe the system would not be attractive to CubeSat developers and would be seldom used. Systems such as camera, radiators, and antennas compete for external surface area. As such, CUBIT's external-facing segment will need to be minimized. Additional hardware may be internalized within the CubeSat and connected to the external unit via a cable. On-Orbit SWaP minimization will affect ground station design. In general, a weaker On-Orbit component will require a larger, more powerful ground component.

<u>Minimal integration with host:</u> Dependence on a relatively unreliable host CubeSat for essential systems such as power and communications reduces the utility of CUBIT and greatly increases the risk of a completely dead CubeSat with no identification methodology available. Additionally, CUBIT will need to be designed to accept different bus voltages (in the case of integrating with host power) or communication protocols (in the case of integration with host communications systems). This would greatly increase development costs. Therefore, we sought to limit integration to a physical-only interface.

<u>Low cost:</u> CubeSats needing an independent identification method such as CUBIT will be the most cash-strapped projects, unable to allot additional resources for performance and verification testing. Additionally, the desire to promote wide-scale adoption prompted SRI to develop a solution consisting mostly of low-cost COTS components. This decision also enables International Traffic in Arms Regulations (ITAR) compliance and promotes the export of the technology to other nations with space launch capabilities.

Due to SRI's extensive background in RF systems for space applications and ground stations located throughout the world, a radio-based method is proposed.

Key Design Attributes

With these drivers in mind, SRI set about designing the CUBIT system. Key design attributes are presented in Table 1. The two-part system (Figure 2) consists of an internally mounted Electronics Unit (EU) and an externally mounted Antenna Unit (AU).

Table 1: CUBIT Tag Data Sheet

Feature	Value
Electronics Unit (EU) size (mounted internally)	~41 mm x 20 mm x 18 mm
Antenna Unit (AU) size (mounted externally)	~ 20 mm x 30 mm
Mass	21 grams
Mounting	Two #0-80 screws, EU orientation unrestricted
Operational frequency	915 MHz
Transmit power	~0.01W, for 20 ms per each interrogation received
Transmissions per orbit	25/orbit. Tag will only transmit when interrogated by ground station, for total of 500ms.
Battery characteristics	110mAh @3.7V
RF inhibits	Timer: 45 min delay of tag function after launch Command inhibit: Will only transmit when interrogated by SRI ground station (coded command).
Deployment power inhibits	Photocell inhibits between Power Supply and EU

Figure 2. CUBIT CAD model showing the two-part system: EU (left) and AU (right).

The EU consists of (1) an aluminum enclosure that houses the main battery, capable of supplying CUBIT with 30 days of power and sufficient to provide identification data during the critical mass CubeSat deployment phase, and (2) the electronics board. While the standard implementation of the CUBIT is with a standalone power supply, the system may be used with internal satellite power for prolonged operations. The EU is designed to fit in a small volume within the CubeSat structure. The microprocessor is housed on the electronics board, chosen for its low power consumption and proven performance in extreme environments.

The AU, connected to the EU by a hardline, is externally attached to the CubeSat and consists of a photo cell and antenna. The ISM 900 MHz helical-style antenna is used for receiving the interrogation signal and broadcasting the tag's response.

Inhibit Design

Launch requirements typically specify inactivation of secondary payloads to prevent interference with the launch vehicle. CUBIT employs multiple RF and deployment power inhibits to accomplish this. The photocell works with integrated inhibits to prevent operation prior to CubeSat deployment (a typical PEAPOD launch envelope holds the CubeSat in complete darkness until deployment). CUBIT relies on this method to prevent accidental operation prior to achieving orbit, as shown in Figure 3, a deployment switch block diagram for the CUBIT tag. The slide power switch provides the first inhibit. When switched to the "OFF" position, the power is prevented from flowing to the Field Effect Transistor (FET) switch and Low Drop Out (LDO) regulator. The photocell provides the second inhibit. Ambient light enables power to flow to the MicroController Unit (MCU) and locks the electrical pathway close, enabling operation in both day and night after initial light exposure.

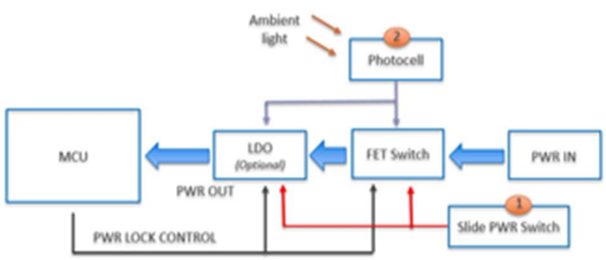

Figure 3. CUBIT inhibit block diagram.

Ground Segment

The On-Orbit system is complemented by the CUBIT ground station hardware. Its current instantiation uses the same chipset to send an interrogation signal through a 10 W amplifier and SRI's 150-ft Dish. The interrogation signal can command a response from all tags, all tags except one specified, or a single specific tag. Figure 4 shows the Ground Station timing.

CONOPs Example

CUBIT is armed prior to deployment by flipping a physical switch while the antenna board's photocell is in darkness, as is typical for a CubeSat within a PEAPOD. After CubeSat deployment, the photocell disengages the power inhibit and initiates a 45-minute time delay, after which the tag is ready to begin receiving interrogation. The interrogation signal is transmitted from SRI's 150-ft Dish at 915 MHz. For a space object with known orbital parameters, the satellite dish can track the assumed location while it is in view, sending interrogation signals for the duration pass within view The received coded command prompts a response by CUBIT and provides, among other things, confirmation of the commanded signal type and the tag's device number. A CUBIT tag response can be received by the interrogation ground station or by other locations, such as the Allen Telescope Array (ATA) located in Hat Creek, CA. Ground station segments can also be set up to enable "fly through" of CubeSats for Space-Fence-like detection and identification. Figure 5 shows a CONOPs example.

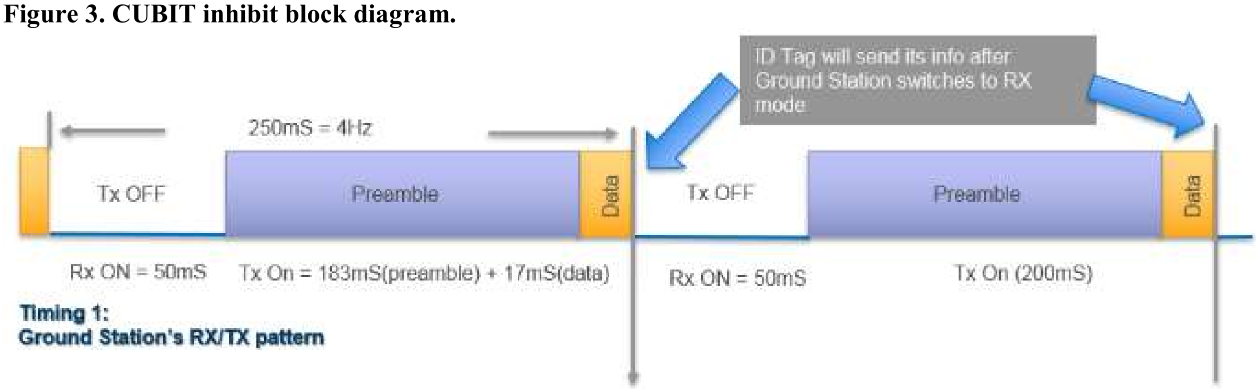

Figure 4. Ground Station timing diagram. The Ground Station system's 50 ms receive window is followed by a 200 ms transmission, which provides the coded interrogation signal.

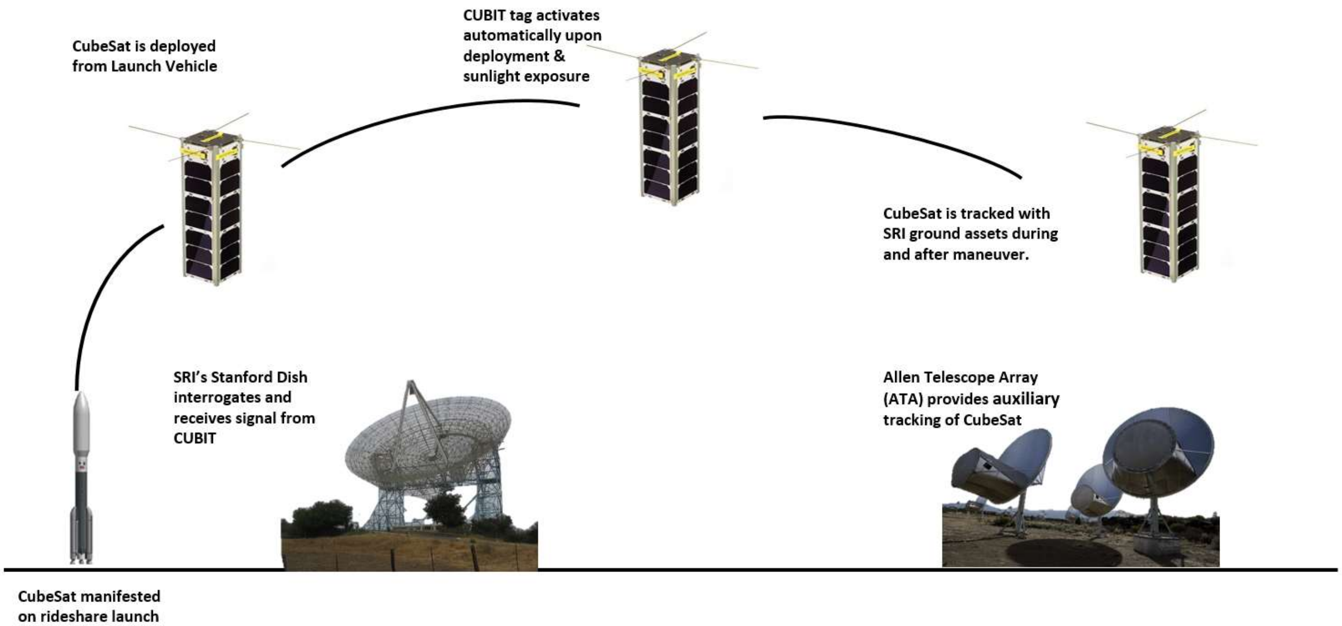

Figure 5. CONOPs example.

ON-ORBIT MISSIONS

On-Orbit Mission 1: TechEdSat 6

Overview. TechEdSat 6 is a NASA-sponsored 3U CubeSat designed to demonstrate a small satellite deorbiting system. NASA Ames graciously hosted the CUBIT tag onboard, enabling SRI to successfully achieve its first On-Orbit demonstration of the technology. One modification from standard CONOPs was that CUBIT was powered by the main satellite power instead of a battery. SRI made this decision because it had high confidence that the main satellite would function and be able to provide power. The removal of the battery also reduced regulatory issues and enabled testing over an extended timeframe greater than what could be provided by the battery.

SRI's CUBIT tag was integrated into the 3U at the base of the satellite. The AU was positioned to reduce the antenna blockage as much as possible. A power and data cable connected the two components, as shown in Figure 6. Configuration was determined through extensive meetings with the primary host.

TechEdSat 6 was launched aboard a Cygnus resupply ship on 12 November 2017 and deployed from the ISS on 20 November 2017 (Figure 7). SRI's 150-ft Dish was used as both transmitter and receiver, and the ATA was used as a receiving ground station (ATA setup is listed in Table 2) to collect at both the CUBIT tag and TES 6 frequency.

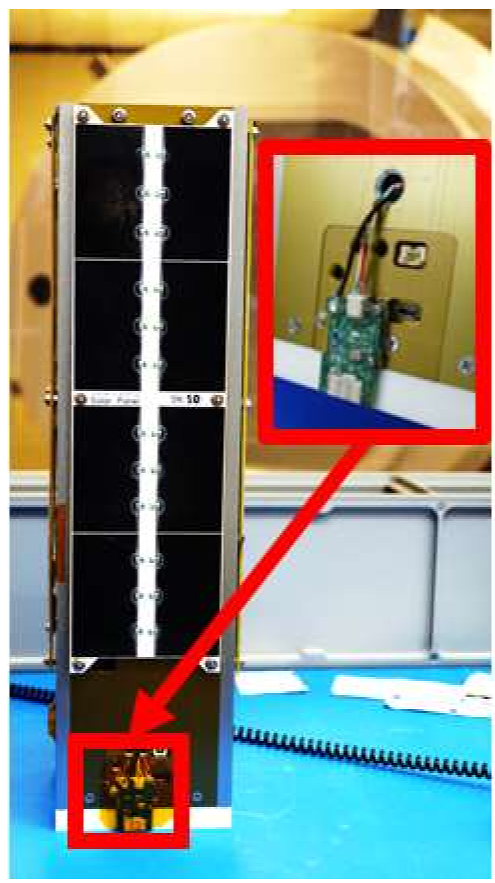

Figure 6. AU placement on the TechEdSat 6.

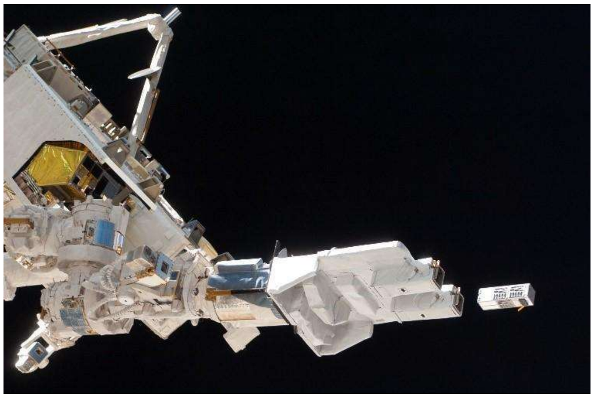

Figure 7. TechEdSat 6 was deployed via the NanoRacks Launcher on 20 November 2017.

Table 2: ATA Setup for TES 6 On-Orbit Demonstration

Feature	Value
Integration size	1 second
Antenna array	10 dishes
Frequency collection center frequency	915 MHz
Bandwidth	3 MHz
Frequency bin	1024 MHz
Frequency collection center frequency	2450 MHz
Bandwidth	100 MHz
Frequency bin	1024
TLE	43026U 98067NK 18005.16510731 .00047214 00000-0 57536-3 0 9990 43026 51.6386 110.2996 0003020 318.6602 41.4163 15.60011722 6993
Pass #1	Rises: > 16.5 deg: Fri Jan 05 02:18:10 PST 2018 Sets: < 16.5 deg: Fri Jan 05 02:21:21 PST 2018
Pass #2	Rises: > 16.5 deg: Fri Jan 05 03:53:41 PST 2018 Sets: < 16.5 deg: Fri Jan 05 03:57:50 PST 2018

Flight Demonstration Results. Throughout the demonstration, the 150-ft Dish was not able to receive the CUBIT return signal from the On-Orbit tag. Figure 8 shows the spectrogram results from the ATA, demonstrating successful tracking and acquisition of the TES6 and its 2.4 GHz beacon. Figure 9 shows a spectrogram emanating from the same location in space a signal at 915 MHz, the frequency of the CUBIT tag. As further evidence, the ATA was set up to acquire time domain data (Direct to Disk Mode). The FSK signal was an exact match of what was expected from an On-Orbit signal from a CUBIT tag (Figure 10).

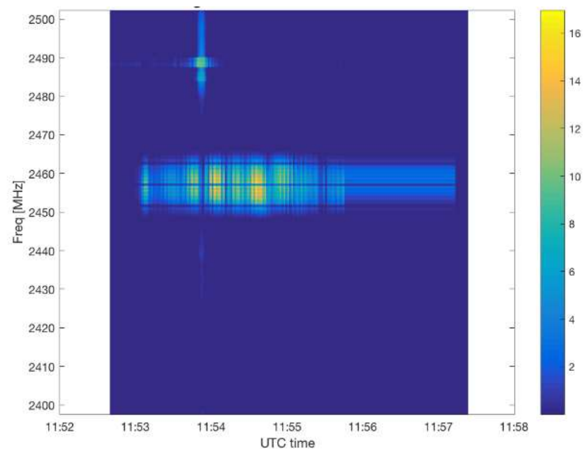

Figure 8. Spectrogram for 2.4 GHz transmission for Pass #2.

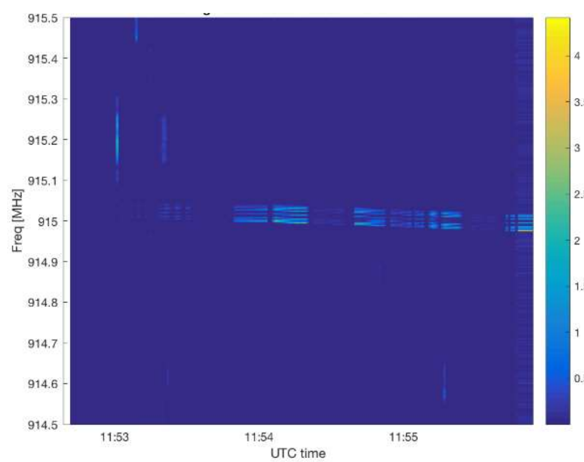

Figure 9. Spectrogram for 915 MHz transmission for Pass #2.

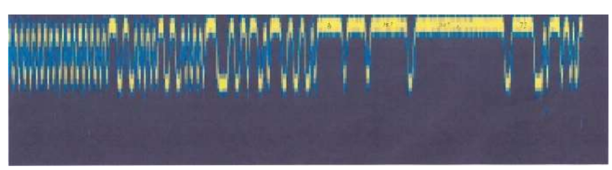

Figure 10. FSK signal received from the TES 6 On-Orbit demonstration.

The TES 6 flight campaign demonstrated the hardware and proof of concept of the CUBIT tag. The CUBIT hardware was able to receive a signal from the ground segment and transmit while On-Orbit the appropriate response.

On-Orbit Mission 2: SSO-A Flight

Overview. SRI International was approached by a US Government official to assist in providing tracking and identification information for passive CubeSats to be launched onboard Spaceflight's Sun Synchronous Orbit rideshare flight (SSO-A). This was to be the largest single rideshare mission from a U.S.-based launch vehicle. The presence of more than one passive CubeSat, with no identification features, as well as the possibility of several DOA satellites during the launch of 64 CubeSats, was the use case for which CUBIT was designed.

In partnership with Elysium Space, Inc. and Southern Star Group, LLC, SRI's CUBIT tags were hosted onboard their passive CubeSats, Elysium Star 2 and Enoch, respectively (Figure 11 and Figure 12). The deployment of two CUBITs simultaneously would demonstrate the CONOPs developed by SRI on CUBIT's operation.

The CUBITs for this flight would be battery powered and in their final configuration. SRI provided general guidance on antenna placement and overall configuration, but final placement was at the sole discretion of the CubeSat developers. This level of guidance would more closely mimic future interactions should CUBIT be used widely, and would result in a range of antenna placements that would impact identification performance. Figure 11 and Figure 12 show CubeSat and antenna placement.

Figure 11. Elysium Star 2, a 1U CubeSat developed by Elysium Space, Inc., contains the ashes of individuals and serves as a memorial.

Figure 12. Enoch, a 3U passive satellite developed by Southern Stars Group in partnership with Pumpkin and sponsored by the Los Angeles County Museum of Art (LACMA), is an urn designed by artist Tavares Strachan to honor Robert H. Lawrence, Jr., the first African American selected to train as an astronaut, who died in 1967 during an aircraft crash.

Regulatory confusion on radio licensing for the Government-sponsored CUBI prevented Elysium Star 2 from receiving deployment authority, and only Enoch was allowed to deploy. Although simultaneous deployment and discrimination were not demonstrated, value was still gained because the CUBIT power system, the only main On-Orbit hardware yet proven in space, was validated.

Flight Demonstration Results. SSO-A was launched from Vandenberg Air Force Base on 3 December 2018. Telemetry from the deployer provided doubt on whether Enoch was successfully deployed from the launcher. Launcher telemetry indicated the POD door containing the Enoch satellite opened, but the signal indicating full extension of the deployment spring was not received. Furthermore, the radar count for number of objects was initially one fewer than expected. A CUBIT collection event on 4 December 2018 was positive, suggesting that the CubeSat at least partially deployed, exposing the CUBIT tag to enable sufficient sunlight for activation. At that point, the deployed satellites were not sufficiently separated to attribute which radar object was Enoch.

Figure 13 shows the data collected from the ATA while it was tracking object 43777 on 4 January 2019. This, along with object count number equaling the number of expected objects, provided proof that Enoch had deployed correctly and was object 43777. This flight demonstration proved CUBIT could operate as intended: as a completely separate beacon that can aid in satellite identification. As of this writing (2 May 2019), 19 of the 65 objects associated with SSO-A have still not been identified.

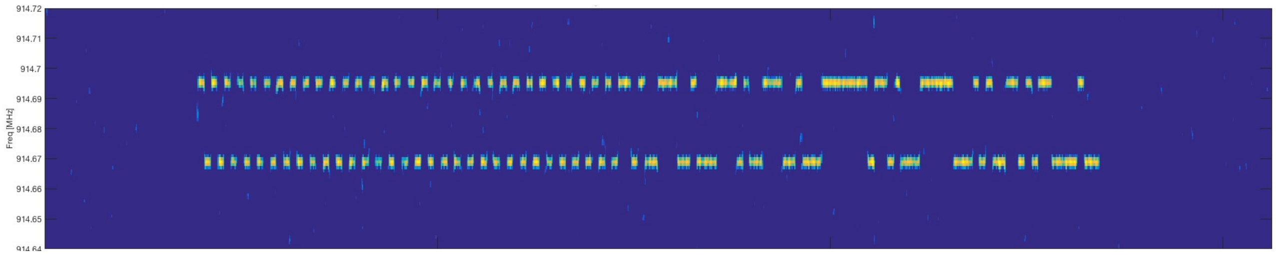

Figure 13. Data from ATA collections for the Enoch flight on 4 January 2019. RF time domain data at 915 MHz shows a near identical "up-down" signature of the CUBIT tag as expected.

SUMMARY

CubeSat identification is a crucial matter for the community, especially as CubeSats increase in number and clustered deployments become more commonplace. While improving, the risk posture and reliability of CubeSats call for an independent method to identify CubeSats after launch.

The CUBIT system has been demonstrated in space and is proven to help identify CubeSats after launch. CUBIT tags have been integrated into a variety of satellites and other space-destined objects, demonstrating its ability to be easily added to existing systems with minimal modifications to the host (Table 3).

Table 3: List of CUBIT Integration Efforts to Date

Host Payload	Host Type	Date of Effort	Status
TES6	3U CubeSat	2016-2017	Launched to LEO Nov 2017. Successful acquisition
ORS-6	Smallsat (300 kg)	2016-2017	De-integrated following primary payload delay
Rocket Lab	Rocket body	2016-2017	De-integrated following White House Office of Science and Technology Policy intervention
NASA FOP	Balloon	2017	De-integrated following flight delays
Elysium Star	3U CubeSat	2018	Launched Dec 2018, not deployed
Enoch	1U CubeSat	2018	Launched Dec 2018, successful acquisition
TES7	2U CubeSat	2018-2019	Pending launch Q3 2019 (Est)

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- NASA Ames, for partnering with SRI and hosting CUBIT on board TES6.
- Elysium Space, Inc., for hosting CUBIT onboard Elysium Star 2.
- Southern Stars Group, LLC, for hosting CUBIT onboard Enoch.
- 18th Space Control Squadron, for working with SRI and providing tracking data.
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