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ELROI: A license plate for satellites that anyone can read

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ABSTRACT

The Extremely Low-Resource Optical Identifier (ELROI) beacon is a concept for a milliwatt optical “license plate” that can provide unique ID numbers for everything that goes into space. Using photon counting to enable extreme background rejection in real time, the ID number can be read from the ground in a few minutes by anyone with a small tracking telescope and a photon-counting sensor. ELROI is powered by its own small solar cell, and it is sufficiently compact, lightweight, and inexpensive for use on CubeSats and other small satellites. The ELROI concept has been validated in long-range ground tests, and orbital prototypes are scheduled for launch in 2018 and beyond, including a PC-104 form factor unit which was integrated into a CubeSat and is scheduled to launch in summer 2018. We describe the design and signal characteristics of this prototype and the next generation of fully autonomous units, and discuss applications for CubeSats and other small satellites.

INTRODUCTION

The Extremely Low-Resource Optical Identifier (ELROI) beacon is a concept for a milliwatt optical “license plate” that can provide unique ID numbers for everything that goes into space[1–3]. ELROI is designed to help address the problem of space object identification (SOI) in the crowded space around the Earth, where over 16,000 active and debris objects are currently tracked. Tracking these objects requires continuous knowledge of each object's position and trajectory, and re-identifying a lost object is significantly easier if it carries an ID beacon that can be read from the ground. Small satellites such as CubeSats are also being launched in increasingly larger groups, and a typical CubeSat operator cannot identify their own satellite immediately after launch without a beacon. There is currently no standard beacon technology that is small and light enough for the smallest satellites, and radio beacons have the additional drawback of RF interference.

ELROI is a small, autonomous optical beacon that uses short flashes of laser light to encode a unique ID number (Figure 1) which can be read from the ground by anyone with a small tracking telescope and a photon-counting sensor. ELROI is smaller and lighter than a typical radio beacon, it is powered by its own small solar cell, and it can safely operate for the entire orbital lifetime of the host object. Using spectral filtering and photon counting to enable extreme background rejection in real time, the ID number can be uniquely identified in a few minutes, even if the ground station detects only a few photons per second. The ELROI concept has been validated in long-range ground tests, and orbital prototypes are scheduled for launch in 2018 and beyond. A comprehensive overview of the ELROI encoding/decoding scheme and applications may be found in other references[3,4]. This paper will briefly describe the design and signal characteristics of the current generation of ELROI prototypes, and discuss applications for CubeSats and other small satellites.

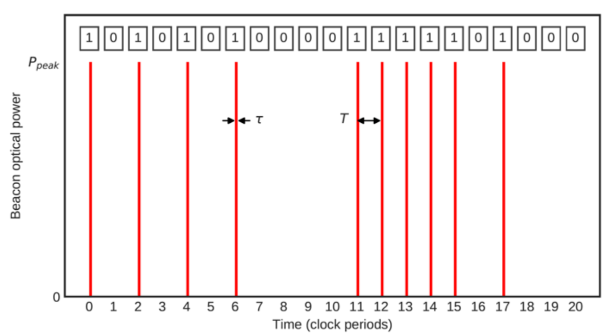

Figure 1: Illustration of the signal produced by an ELROI beacon. The onboard laser diode emits short pulses of light (pulse width τ) separated by a fixed period (clock period T). Each clock period encodes one bit of the beacon ID number. The precise timing and high peak power of the signal pulses enable extreme background techniques that allow the ID number to recovered in single orbital pass even if only a few photons per second are detected at a ground station.

APPLICATIONS FOR SMALL SATELLITES

The primary purpose of ELROI is to simplify space object identification (SOI) when an object is tracked but not identified. Because most satellites and debris cannot be easily identified without matching them to a radar track that has been maintained continuously from launch, an "uncorrelated track" can occur when radar or other observations are interrupted, when solar activity causes sudden increases in atmospheric drag, when satellites make unexpected maneuvers, or when two orbits become nearly identical.

By enabling rapid optical identification, ELROI reduces the number of costly observations that may be needed to resolve these uncorrelated tracks in radar systems, freeing up resources to monitor new objects and potential threats. ELROI is small and light enough for CubeSats and other small satellites, and we expect the unit price of the mature ELROI design (in the $1k range) to be accessible to educational CubeSat operators. ELROI also provides additional benefits to small satellite operators that may drive voluntary adoption, as discussed below.

Rapid post-deployment identification

Small satellites, particularly CubeSats, are often launched and deployed in groups ranging from a dozen to more than a hundred satellites[5,6]. A typical CubeSat operator does not have the resources to determine which of the resulting radar objects is their satellite, particularly in the period immediately after deployment when all the deployed objects are in nearly identical orbits. This can have important consequences for troubleshooting and anomaly resolution—for example, if the satellite is not communicating with a ground station as expected, and it cannot be verified that the satellite exited the dispenser. A CubeSat with an ELROI beacon could be identified as soon as it is visible from a suitable ground station, even in a crowded field containing multiple objects from the same launch.

Black box for anomaly resolution

For a small amount of added optical power, the ELROI encoding scheme can transmit additional low-bandwidth information beyond the ID number. Auxiliary data bits may be interleaved as additional laser pulses out of phase with the ID bits (recall Figure 1). Like the ID number, this information could be read by anyone with a suitable ground station.

One application of this auxiliary data channel is to provide "black box" information for diagnosing and recovering from spacecraft anomalies without radio communication. Because the ELROI unit is autonomous and self-powered, it may continue to transmit even if systems in the host satellite fail. With a data connection to the host, an ELROI beacon could transmit low-bandwidth state-of-health information. Even with no direct connection to the host, the beacon could transmit information from its own small sensors (e.g., MEMS accelerometers or temperature sensors). Variations in beacon solar cell voltage also convey information about attitude and spin rate. Thus, ELROI beacons could add significant value to small satellites by increasing the chance for anomaly resolution and by providing more data on spacecraft malfunctions to improve future designs.

Example link budget for a CubeSat host

The sensitivity of the ELROI ID measurement relies on the use of a photon-counting detector. (Due to read noise, the ELROI ID cannot be recovered with a conventional CCD camera.) Each photon registered by the detector must produce a discrete signal with time resolution better than the pulse width τ (Figure 1). Our current ground station uses a LANL-developed photon-counting camera, which has a large-format sensor. Arrays of SPADs, position-sensitive readouts for PMTs, and other technologies can also provide spatial resolution. An imaging detector is not required to observe ELROI if the telescope tracking is sufficiently accurate to keep the host satellite within a small field of view for the duration of an observation.

The optical link budget gives the expected photon detection rate at a ground station. The count rate in photons/second measured by the receiver is

$$R = P_{\text{avg}} \times 1/\Omega \times A/r^2 \times T_{\text{tot}} \times \varepsilon_{\text{DQE}}/E_\gamma \qquad (1)$$

P_{avg} is the average power of the beacon, determined by the peak power P_{peak} and the duty cycle d. Ω is the solid angle of the beacon emission. A is the collecting area of the receiver optics, and r is the distance from the beacon to the receiver. T_{tot} is the total optical transmission, including the spectral filter transmission and the atmosphere transmission. ε_{DQE} is the quantum efficiency of the photon-counting detector, which has been measured to be 3.9% for the LANL sensor. E_γ is the energy per photon at the beacon wavelength.

For a red (638 nm) beacon with average power $P_{\text{avg}} =$ 2 mW, observed at 1000 km range by our ground station with a 10-nm bandpass filter, we expect to detect about 3.3 photons/second[3], which is sufficient to recover the ID number with 50-100 seconds of observation. Reflected sunlight from the host satellite is the dominant source of background photons. Modeling a 1U CubeSat as a 10-cm sphere illuminated at a 90° phase angle ("half moon"), we expect to detect about 0.4 background photons/second.

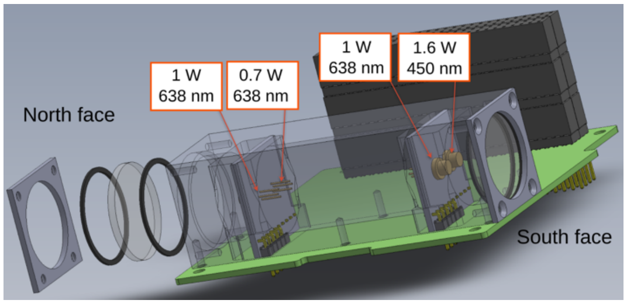

Figure 2: Components of the ELROI-PC104 board, with laser diodes shown.

ELROI-PC104

ELROI-PC104 is a prototype designed in a standard PC-104 form factor, a common footprint for CubeSat payloads. Although the mature version of ELROI is designed to be autonomous and powered by its own small solar cell, this prototype receives power from the host satellite. It carries four laser diodes on two opposite faces of the satellite (Figure 2).

The ELROI-PC104 payload was built at Los Alamos National Laboratory and delivered in 2017 for integration into NMTSat, a 3U CubeSat designed and built by students at New Mexico Institute of Mining and Technology in Socorro, NM[7]. NMTSat is funded by the NASA ELaNa CubeSat Launch initiative and is scheduled to launch on a Rocket Lab Electron mission in summer 2018. Additional technical details about ELROI-PC104 and its integration into NMTSat may be found in a previous reference[4].

After launch, we will observe ELROI-PC104 from a Los Alamos National Laboratory ground station at Fenton Hill, near Jemez Springs, NM. Our receiver consists of a 36-cm aperture commercial telescope, optical bandpass filters, computerized mount, and a LANL-developed photon-counting camera[8]. Less expensive single- or few-element photon-counting sensors may also be used to observe ELROI, with correspondingly stricter requirements on the tracking and pointing accuracy of the telescope and mount system[4]. We encourage others to consider observing this test flight and future flights.

ELROI-UP

The ELROI Universal Prototype (ELROI-UP) is a more advanced, fully autonomous design that is currently in final assembly and environmental testing (Figure 3).

ELROI-UP carries its own small solar cell, and can receive power and commands from a host satellite, but does not require them. ELROI-UP can contain up to four laser diodes. The first test flight units will be populated with four 638-nm red laser diodes with peak power 2.5 W. Different combinations of the four emitters will be pre-programmed to allow testing at up to 10 W peak power. Each diode was measured to emit over approximately 1.3π steradians solid angle.

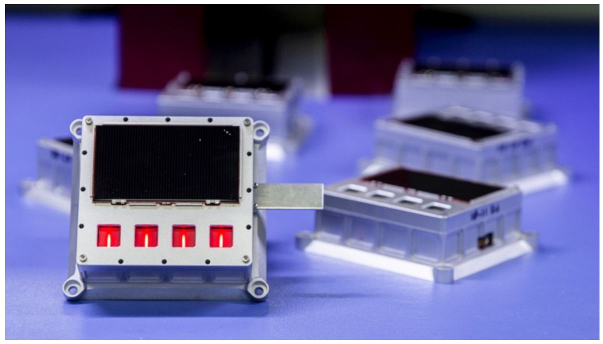

Figure 3: ELROI-UP units.

ELROI-UP is 98 × 92 × 34 mm in size, its mass is 250 g, and the power (if externally supplied instead of provided by the solar cell) is less than 100 mW.

ELROI-UP is designed to be attached to any host that can accommodate it. The unit can also be mounted in a passive mechanical structure and launched as a free-flying CubeSat in 1/3U, 1/2U or larger form factor. We are willing to provide these units to interested launch opportunities.

ELROI 1.0

The final target size of the mature ELROI design is a few centimeters square, similar to a thick postage stamp. The minimum size is limited by the solar cell needed to power the laser diode(s). A concept illustration is shown in Figure 4. This design will be suitable for the majority of low-Earth orbit (LEO) CubeSats and many larger satellites. Larger, higher-power designs may be used for some larger or more distant satellites.

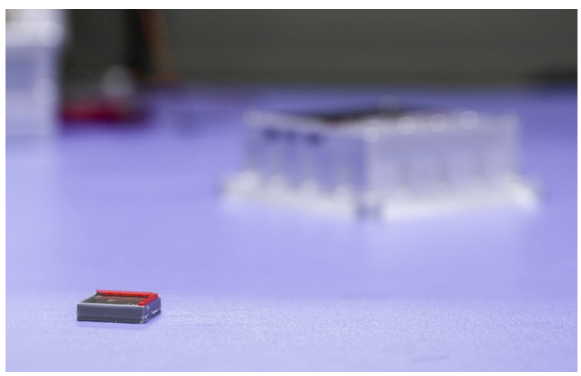

Figure 4: Concept design of an ELROI 1.0 unit compared to ELROI-UP.

Acknowledgments
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