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Progress Towards the ELROI™ Satellite License Plate

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ABSTRACT

The ELROI™ System, (Extremely Low Resource Optical Identifier), uses a beacon that could be attached to any object that goes into space and provide a persistent identifier to the space object that can be read out by a small telescope on the ground. This could alleviate the approaching crisis in Space Traffic Management caused by mass launches of small satellites and the formation of large constellations. Identification beacons on all future space objects will simplify satellite operations and greatly relieve our overstressed space tracking and traffic management infrastructure.

This paper provides information on the current status and future plans for the ELROI™ system, as well as a discussion of common questions and concerns regarding the proposal. The applicability of the system in different orbital regimes, the difficulties and value of implementing it, and its effect on optical astronomy (surprisingly little!) are covered.

INTRODUCTION

With the profusion of SmallSats, with double- and triple-digit numbers of satellites per launch, and quadruple- and quintuple-digit numbers per constellation, the Space Traffic Management (STM) situation is approaching a crisis. Space Object Identification (SOI) is an essential part of STM; we need an accurate and reliable way to determine the identification of a space object, whether it is one of a cloud released by a launcher or an unidentified blip that shows up on radar or in a telescope.

The ELROI™ System (Extremely Low Resource Optical Identifier) is a proposed solution to parts of the SOI problem.[1-4] The system uses a small light-emitting beacon that can be attached to any object that goes into space. The beacon flashes out a serial number that can be read by a small telescope on the ground, uniquely identifying the object. With only a few milliwatts of light required for a LEO CubeSat, the beacon can be self-powered by a small solar cell and battery that will allow the entire autonomous beacon to be built into a Scrabble-tile-sized package.

The beacon's small size and simplicity make it an acceptable addition even for the smallest satellite. Its autonomy will allow it to be attached to debris objects such as rocket bodies that don't have power or communication systems. Because it is an optical system it doesn't produce any radio frequency interference, and may be left running even after the end-of-mission of the satellite, providing a confident identification from launch until the satellite re-enters.

However, because it is not a conventional high-powered radio emitter, it requires specialized readout techniques with dedicated observations by sensitive equipment which only works under clear nighttime skies at the detector. The system is intended to supplement, rather than replace, the current range of techniques for SOI and STM.

Several satellite-powered prototype beacon units have been delivered, and one has been launched into orbit. Unfortunately, that satellite did not wake up after launch, and the other satellites are delayed until 2021. We are currently working towards a fully-autonomous unit that will not be dependent on spacecraft systems, and shrinking the prototype units to a size closer to the eventual Scrabble-tile goal.

Commonly raised questions about the usability and reliability of the ELROI™ system, and its effect on ground-based astronomy, are also covered in this paper.

™ ELROI is a trademark of Los Alamos National Laboratory.

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BACKGROUND: THE ELROI™ CONCEPT

(This section of the paper has been previously published in the references[4] and is repeated here as a courtesy to the reader)

The ELROI™ signal is produced by high-power laser diodes that are diffused to emit over a wide angular range so that they can be seen from a wide area on the ground. These diodes emit very short flashes of light hundreds of times per second, with precise timing, to encode a satellite's serial number. Because the flashes are so brief the lasers are off 99.9% of the time and so average draw only a few milliwatts of power. This minimal power can be supplied by a few square centimeters of solar cell plus a battery (the size you would find in a wrist-watch) to keep operating through orbital night. The low power, and the simplicity of the required circuitry, will allow the beacon to be packaged as low cost, small, lightweight self-contained unit that can fit the size, weight, power, integration, and economic budget of even the smallest CubeSat.

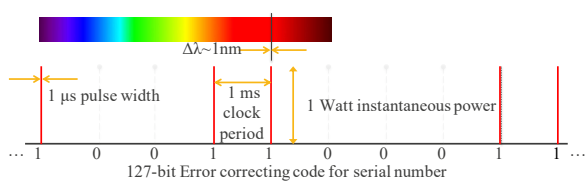

Figure 1 The ELROI™ signal—brief, bright pulses of monochromatic light on a periodic clock interval with a repeating error-correcting code—allows extreme background rejection and permits a very low power signal to be recovered despite otherwise overwhelming background.[2]

The signal is received by pointing a small telescope at the satellite and using a single-photon detector to recover the timing of the beacon's emitted light. Our ground station is a 35-cm aperture telescope (a size used by serious amateur astronomers) with a specialized detector developed by our group at Los Alamos National Laboratory (although commercial equivalents are available). This system is appropriately sized to determine the beacon's serial number during a single overhead pass of a LEO satellite with several minutes of observation. Engineering trade-offs can be made between size and pointing accuracy of the telescope, complexity and efficiency of the detector, orbital regime, observation time, and telescope location.

The timing, coding, and spectral characteristics of the signal allow "extreme background rejection" to distinguish the beacon photons from sunlight bouncing off the satellite and determine the satellite identification number with very high reliability.

Successful ground tests[1] validated the concept at a range of 15 km using attenuators and reduced-size optics to simulate the expected signal strength at satellite-to-ground distances. These tests demonstrated that ELROI™ signals of a few photons per second can be extracted from data taken at much higher background levels and that the encoded registration number can be confidently identified.

The ELROI™ signal is intentionally open and accessible to anyone with a ground station. The ID of each beacon will be stored in an open registry, along with contact information for its operator and other information. This allows the ELROI™ system to be adopted as an international standard, read by ground stations around the world to assist in the worldwide problem of STM. The beacon can transmit additional data beyond the ID, giving satellite operators a backup channel for anomaly resolution and other diagnostic purposes. This, along with the benefits to the spacecraft operator of being able to identify their own satellite, can drive adoption of the system even in the absence of international norms or mandates.

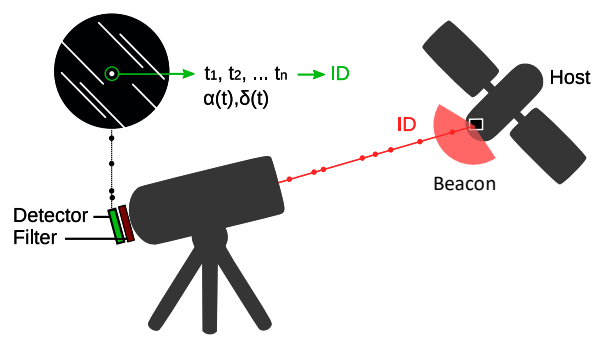

Figure 2 Overview of the ELROI™ system. The beacon is attached to a satellite and continuously emits its optical signal—encoding a unique ID number—over a wide solid angle. A ground telescope collects a small portion of the emitted photons, which are detected with a photon-counting sensor. A narrowband filter centered on the beacon wavelength rejects background light. The recorded data (circular inset) consists of a list of photon detection times at a tracked location (green circle). Streaks represent background stars. The data analysis technique uses the timing characteristics of the ELROI™ signal to eliminate more than 99% of background photons, making it possible to read the ID in a single pass even if the signal is only a few photons per second.

CURRENT STATUS AND PLANNED PROGRESS

First flight of an ELROI™ beacon unit

The first ELROI™ beacon in space was integrated into the New Mexico Institute of Technology's NMTSat, a 3U CubeSat built for educational purposes. As discussed in last-year's SmallSat conference paper[4] this satellite was one of 13 satellites (plus two rocket stages) that were launched into orbit in late 2018. 7 of the satellites were contacted by radio and identified with individual satellite orbits provided by US Air Force 18th Space Control Squadron (on www.space-track.org), but NMTSat is among the 6 that have not been contacted.

We observed all satellites following the launch, later concentrating on the 6 unidentified orbital tracks, to see if we could detect the ELROI™ signal from any of them. (There are plausible failure modes that would prevent radio contact with NMTSat while still allowing the beacon to function.)

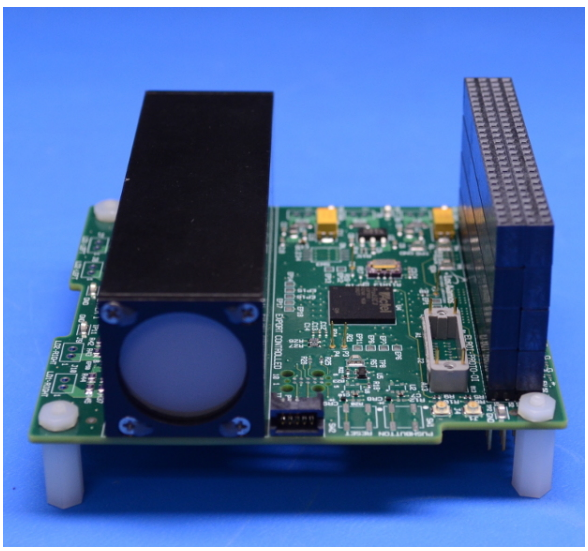

Figure 3 The ELROI-PC104™ beacon unit that was installed on NMTSat.

No ELROI™ signal was detected from any of the unidentified objects. Three of the satellites were observed to have periodic (~3–10 s) lightcurve fluctuations that are typical of unstabilized CubeSats in their equilibrium rotational state. Because NMTSat is passively stabilized with a damped bar magnet, it is most likely that it is one of the satellites not observed to be blinking (#43854, 43859, or 43862 in the catalog).

Our current belief is that NMTSat never turned on after launch.

Planned Launches

Two ELROI™ beacons were delivered in August, 2018 for launch on the Laser Communications Experiment (LaCE), a pair of research satellites being developed by the Naval Information Warfare System Command. These units are powered by the spacecraft to allow them to turn the units on and off, to eliminate the potential for interference with the laser communication tests. These satellites are currently planned to launch in April, 2021.

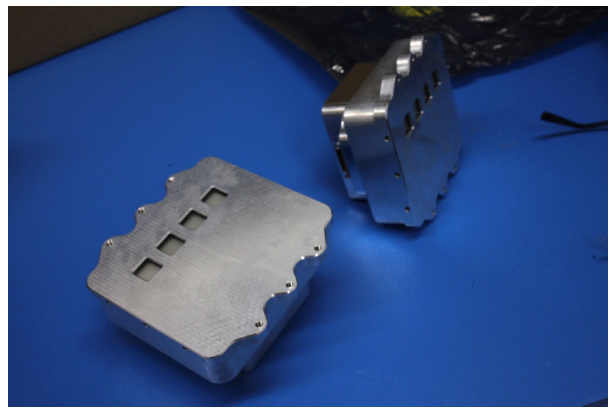

Figure 4 Two ELROI™ beacon units delivered for a launch in 2021.

We will be delivering an additional satellite-powered ELROI™ beacon unit later this year to the Air Force Institute of Technology for incorporation into their Grissom-1 CubeSat, for launch in early 2022.

These launch opportunities are provided by the DoD's Space Test Program.

Your satellite!

We are looking for additional flight opportunities. If you wish to fly an ELROI™ beacon, please contact the author. Our current prototype units are roughly 1/3 U and can be powered by its own solar cell or the spacecraft bus, and can operate fully autonomously or under spacecraft command and control. Future development (see below) will produce smaller ELROI™ beacons.

Your ground station!

We also invite any potential ground station operators to take a look at our beacons after they launch. This requires the ability to track a satellite with a small (30 cm or larger) telescope and take and analyze data from a single-photon detector.

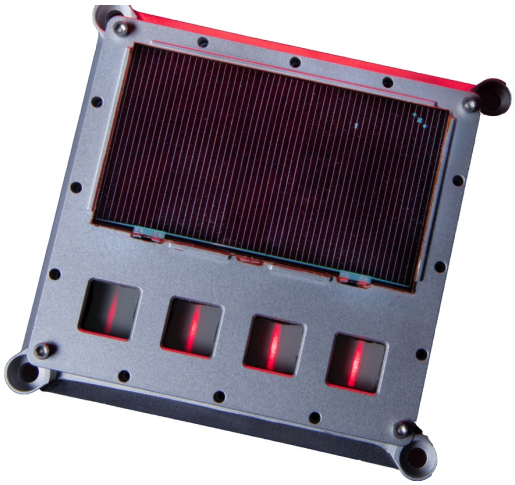

Figure 5 Autonomous solar-powered ELROI™ units available for future flights on your satellite.

Future development

Los Alamos National Laboratory, through its Feynman Center for Innovation, has released a call for proposals from commercial partners to develop the next generation of the beacon.[5] (The deadline for proposals is June 30, 2020.)

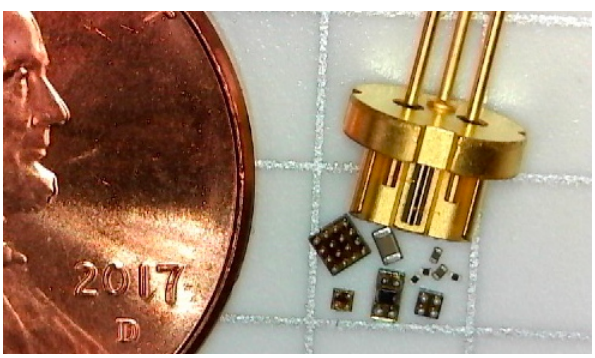

Figure 6 The additional electronic components required for a built-in spacecraft-powered ELROI™ beacon are shown here. 5 mm² grid and US 1¢ coin included for scale.

It is expected that the beacon can be built as a fully autonomous unit of a few square centimeters (area dominated by the solar panel) and less than a centimeter thick (volume dominated by the battery). Alternatively, the ELROI™ capability can be added to a spacecraft design with a small number of small components powered by the spacecraft power systems (Fig 6).

QUESTIONS AND CONCERNS

There have been a number of questions regarding the ELROI™ system, and this publication is a good place to address them.

Is the ELROI™ system The Solution to the Space Traffic Management problem?

Not alone. The ELROI™ system is a useful component in the Space Object Identification task. The system can be used to untangle the snarl of orbital tracks resulting from a mass launch, or to identify an unknown object found in space surveillance.

Once the ELROI™ system or other techniques have identified individual satellites, continuous all-sky scans by, *e.g.*, the Space Fence can maintain track custody to keep all space objects identified. Identification of individual objects, giving values for characteristics like their area-to-mass ratio, improves the orbital propagation estimates to allow better track custody maintenance compared to attempting to correlate successive passes of unknown objects. The availability of the ELROI™ system also relaxes the requirements on these scans and improves their utility by providing a recovery mechanism for objects that get lost.

Is this only for CubeSats?

No. Variants of the ELROI™ beacon can be designed for larger satellites, although they may require more power. The signal-to-noise calculations presented in the original paper[1] show that a milliwatt-level optical transmission can be detected against the sunlight reflected by a CubeSat, but once the effective size of reflective area of the satellite approaches a square meter or more, it is worthwhile to increase the transmission power.

This requires correspondingly larger solar cells, battery, and laser emitters. However, the scaled size of the beacon grows much more slowly than the satellite itself for a given Signal to Noise Ratio (SNR).

(If more powerful beacons are developed, it may be a good decision in some cases to use them even on CubeSats, to increase the identification reliability or decrease the required ground station contact duration.)

If the satellite is not sunlit (eclipse conditions) the satellite size is irrelevant, as the signal does not need to compete against reflected sunlight.

What are the limitations (and advantages) of an optical beacon compared to radio techniques?

An optical beacon of this type requires a telescope to be pointed at the satellite, and the ground station must be under clear nighttime skies. Thus, the optical beacon can only be used to determine the identity of an object whose orbit has previously been determined.

In contrast, a sufficiently-powerful radio beacon could be picked up by an omnidirectional directional antenna, at any time of day or night, under almost any weather conditions, whenever the satellite is well above the horizon. However, for an optical beacon there is no danger in confusing the IDs of two satellites even if they are quite close together (limit ~10 meters), while the radio beacon signals can overlap and be confused.

A 'sufficiently powerful radio beacon' does require much more power and other resources than the ELROI™ beacon, and is also a significant source of Radio Frequency Interference (RFI). RFI concerns should prevent such a beacon from broadcasting at all times throughout the orbital life of every space object, while there are no such limits on optical beacons.

How hard is it to set up a ground station?

A ground station is a telescope, on a mount that can point at a satellite, equipped with a single-photon detector. These are all commercially available items in mass production. However, they require significant expertise to combine into a working system. This expertise has been developed for similar tasks.

Satellite Laser Ranging (SLR; overview at[6]) requires the use of tracking telescopes to point a laser at a satellite, receive the reflected light, and precisely time the arrival of the received photons to determine the distance to the satellite.

Satellite-to-ground optical communications requires the satellite to point a laser at the ground station, and the ground station to point a telescope at the satellite. This is done at a considerably higher received power than either ELROI™ tracking or SLR, so daytime operation is possible and the telescope tracking can guide on the incoming signal.

When a satellite is illuminated by the Sun and the ground station is in darkness (terminator conditions) a conventional CCD or CMOS camera viewing through the telescope can detect the satellite and adjust the telescope pointing accordingly. With the use of a dichroic (wavelength-dependent) pick-off mirror, light from the satellite at the beacon laser's wavelength can be directed onto a small, low-cost, single-photon avalanche diode (SPAD) or other low-noise detector.

When the satellite is not illuminated by the Sun (eclipse conditions) it is rare that sufficiently-accurate orbital information is available to point the telescope and get its light on a small SPAD without feedback from a camera. Under these conditions, an imaging photon counting detector can be used to measure all photons within a larger field of view. The data is then analyzed at each point in the field of view, corresponding to an orbital error offset, until an ELROI™ signal is detected. These imaging detectors are commercially available, but they are manufactured at low volume and at high prices that can be a significant fraction of the capital cost of a ground station.

Therefore, the first ground stations may initially be SPAD-based systems that only work under terminator conditions. A new imaging technology, the SPAD array, is currently under intensive development (driven by the expected need for automotive LIDAR) and may provide a low-cost alternative to the current generation of single photon imagers. SPADs are also more sensitive (higher quantum efficiency – QE) than the current single photon imagers.

How many ground stations do you need and where do you put them?

Three stations is probably the minimum for initial operational capability, and six would be better. With increased demand, more locations can be added, or additional telescopes can be added to the same locations.

For a LEO orbit, the opportunity to observe a satellite under terminator or eclipse conditions on any given day varies with latitude, time of year, and where the satellite is in its nodal precession cycle. Thus, a given ground station may not be able to observe a given satellite for several weeks or longer, even absent weather considerations.

To provide coverage of all satellites on a timescale of a day or so, multiple ground stations must be distributed at different latitudes in the Northern and Southern hemispheres. To reduce the timescale to below a day, and to reduce the effects of weather, distributing additional stations in longitude would help.

Economically, it would make the most sense for ground stations to be fully-automated and co-located with other satellite ground stations or telescope facilities to provide infrastructure and maintenance support. Due to the ELROI™ system's excellent noise rejection, astronomical-quality sites (with very dark skies, extreme altitude, and low-turbulence seeing) are not necessary, although downtown locations in major light-polluted cities should be avoided.

What if the ELROI™ emitter doesn't point at the ground station, or the solar panel doesn't point at the Sun?

If the laser emitters do not illuminate the ground station, or the solar panels do not provide enough power to keep the battery charged, the ELROI™ system will not be able to provide an identification. There are several potential strategies for dealing with this:

- Put multiple solar cells and emitters on different sides of the spacecraft so that one or more is always well-positioned. This can be implemented, *e.g.,* as a single ELROI™ core connected to remote solar panels and emitters; or multiple coordinated ELROI™ beacon units sharing power and timing signals over a cable.
- Accept the reliability level provided by the natural tumble of an unstabilized satellite. Due to the continuous repetition of the ELROI™ signal, the identification can be reconstructed even if the emitter points at the ground station intermittently during the pass, but there will be spin states and orbital geometries where the emitter avoids pointing at the ground station throughout the pass. If the ID is not recovered during a pass, a second or third observation—viewing the satellite from other angles—may recover it. However, this strategy will give a lower overall reliability at higher observation costs than one which emits in all directions.

The choice of strategy will depend on a cost/benefit judgement including available resources, orbital regime, spacecraft size, and other parameters.

Is this only for Low Earth Orbit (LEO)?

Geosynchronous Earth Orbit (GEO), around 36,000 km from Earth's surface, causes a signal reduction of roughly 3 orders of magnitude compared to nominal LEO operations due to the inverse square law. However, it is possible to regain that loss through several techniques:

- *More optical power in the beacon*. GEO satellites tend to be large and have a lot of power capacity (although CubeSats for that orbit are currently in preparation). The use of hundreds or even thousands of milliwatts of optical power is practical on a large satellite. Because eclipses are infrequent, no battery is needed.
- *Directing some of the light towards Earth.* Most GEO satellites in nominal operation have an Earth-pointing section. Concentrating a significant fraction of the emitted light towards that direction raises the signal under those conditions and simplifies routine operation. The remainder of the emitted light should be spread out in all directions to allow it to be read (less easily) when the satellite is not in that orientation, during anomalies, or after the satellite is retired.
- *Larger telescope on the ground.* Satellites in higher orbit have slower (or no) apparent motion across the sky, reducing the requirements on the telescope mount compared to one capable of chasing and accurately-tracking a fast-moving LEO object. This permits a larger-aperture telescope to be acquired on the same total budget.
- *More sensitive detector.* Because the GEO satellites are almost always in sunlight, and are slow-moving, it is relatively easy to guide the telescope so that the light from the satellite falls on a very small and sensitive detector. (The smaller the SPAD, the lower the noise tends to be, and a SPAD's QE can be an order of magnitude or more higher than the imaging detector we are currently using.)
- *Longer observation times.* A LEO satellite can go from horizon to horizon in five minutes, with only 2-3 minutes of good observation time. A GEO satellite allows arbitrarily long observations to accumulate signal and beat down noise.

These opportunities to increase SNR make the use of the ELROI™ system in higher orbits quite practical.

What are the effects of ELROI™ beacons on ground-based optical astronomy?

This is an important question. However, the light from the beacons will have no significant effect on ground-based astronomy at either the amateur or professional level, except in very limited cases discussed below.

In sunlight, the satellite reflects much more light than is emitted by the beacon attached to it (even in the narrow wavelength band the beacon's laser uses). Therefore, the potential adverse effects (beyond that of the satellite itself) are limited to eclipsed satellites.

Take, as a nominal worst-case set of parameters, a LEO satellite at 500 km distance with a beacon producing 1W peak power during 1 microsecond pulses, once a millisecond, at λ=638 nm into a solid angle of π steradians.

The apparent motion at orbital speeds for this distance is ~3 arcseconds per millisecond. Assuming that the pixel or other detector resolution element size is smaller than

that, only one light pulse will contribute to a given data point, while the next pulse will hit a different element.

The fluence of each pulse at the telescope is 4 photons/m^2. For small telescopes this is obviously unimportant, with less than one photon expected in a 50 cm aperture. For large apertures, the divergence due to the finite distance of the beacon produces a blurred spot with a maximum intensity of 25 photons/square arcsecond for apertures 2.5 m or larger. (For apertures larger than 8 m the blurred spots from successive pulses can merge, but even the Thirty Meter Telescope will see less than 100 photons/square arcsecond.)

For a 2.5 m telescope, in the R band, assuming a 1 second integration time, this corresponds to areal brightness of m_R=23.4 mag/square arcsecond. This is about ten times dimmer than the natural brightness of dark skies at La Palma, a world-class observing site.[7] For longer exposures the beacon light is diluted by time, for larger telescopes the apparent magnitude decreases even further below the sky background, for smaller telescopes the signal is correspondingly reduced, and in color bands not including the laser wavelength the light is filtered out.

For light from an ELROI™ beacon to interfere significantly with an astronomical observation, the observational parameters must combine large aperture, narrow wavelength bandwidth, and high time resolution. The only astronomical endeavor we are familiar with that combines these aspects is Optical Search for Extraterrestrial Intelligence (OSETI). OSETI is looking for short laser pulses from space, and therefore the ELROI™ signal is perfectly designed to be their noise. Even so, most OSETI work has concentrated on looking for nanosecond pulses, and would not see microsecond-long pulses.

CONCLUSIONS

The ELROI™ system will provide a valuable tool for Space Object Identification and Space Traffic Management. Although it did not have a successful first flight, more flights are planned and additional beacon units are available for any additional flight opportunities.

Optical beacons have advantages and disadvantages compared to radio communications or radar continuous track maintenance, which makes them a useful addition to those techniques.

ELROI™ beacons can be applied to all space objects in any orbital regime. It is also safe for astronomy.

There are scientific, engineering, and commercial opportunities available for satellite operators, hardware manufacturers, and ground station operators. Talk to me if you are interested!

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