SATELLITE LICENSE PLATE: SYSTEM MODELLING AND FIRST GROUND-TO-GROUND TESTS

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ABSTRACT

At TNO, a method for cooperative identification of satellite is being developed: the so-called Satellite License Plate (SLP). This method is based on the laser-enabled identification of passive coded tags. The latters could be mounted on the satellites, occupying a relatively small volume (0.02U). In this contribution, the recent progresses on this method are presented. These include the system modelling of the identification process and the results of preliminary ground-to-ground tests.

Keywords: Satellite Identification, Satellite Laser Ranging, End-of-Life Management, Swarm Satellite.

1. INTRODUCTION

In several situations, satellite orbital management can benefit from satellite identification techniques from ground: from identifying single orbital objects from a swarm launch, to detecting anomalous behaviour of satellite and easing its removal. Despite satellite detection is already in place by means of radar systems, and, in case of large platforms, of optical observations, a standardized cooperative identification method is not yet available in the satellite market.
The SLP method presented in this contribution is a fully passive solution based on optical spectral encoding. The idea behind the method is at the basis of its name. Each satellite should be provided with a tag marker which can be optically detected from dedicated ground stations. Translated to the automotive traffic scenario, the method is similar to the vehicle identification by means of license plates. The method proposed employs optical techniques rather than radio frequency techniques. Optical techniques offer several advantages for this application including usage of a relative free spectrum for an additional service, rather than the congested radiofrequency one, no electromagnetic interference with satellite on-board equipment and increased spatial resolution with respect to radar techniques. Optical based identification methods have already been proposed for cooperative identification, among which both active [1], and fully passive [2] solutions.
Differently from the previously mentioned examples, the method here proposed consists of an optical ground station and a wavelength-selective retroreflecting tag. Each satellite should be equipped with a tag which has a unique spectral signature. The chosen concept relies on a fully passive tag, which does not require power supply of thermal control, easing its adoption on payload for satellite providers.
The optical ground station in its architecture resembles the one of a satellite laser ranging system. It consists of laser transmitters, a large aperture telescope, and, connected to it, a receiving terminal. During the passage of an orbital object the ground station interrogates the target with a set of laser beams of different wavelengths. With the proposed tag concept, the retroreflected signal coming from the satellite is characterized by a unique spectral signature, which can be interpreted at the receiving terminal. Moreover, this method can be complemented with more established satellite laser ranging techniques, offering a unique combination of identification and orbital parameters.
The recent research efforts for the TNO-SLP method have been directed towards an initial model assessment of the method, with end-to-end modelling activities, and first assessment of technologies for this concept in a ground-to-ground test. This contribution is organized as follows: in section 2 the end-to-end model developed is described, together with the analyzed scenario, assumptions taken and initial results; in section 3 the ground-to-ground test setup is reported, together with the preliminary experimental results; finally the conclusion and the future perspectives are reported in section 4.

2. END-TO-END SYSTEM MODELLING

To assess the feasibility of the identification method, an end-to-end simulation model has been run. As sketched in Figure 1, different physical models have been combined to consider the various characteristics of the optical ground station (OGS), the satellite orbital propagation, and the receiver electronics and reconstruction algorithm.

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The end-to-end model first calculates the viewing geometry parameters, based on the position of the OGS and of the satellite's orbit. Based on the passage of the satellite, the model identifies a time visibility window within the passage of the satellite on top of the OGS. In a second step of the simulation, the visibility window is sampled in events by the transmitter lasers pulse rate. Depending on the complexity of the code, multiple wavelengths are employed to code each plate. Therefore, multiple laser pulses are launched from the transmitter at the same time, or at least within a single laser period. Each laser pulse is propagated from the transmitter to the target tag and retro-reflected back towards the receiver OGS. To model the complete pulse propagation, available analytical models were used [3]. In the model, the light collected by the OGS impinges on an array of detectors: one for each spectral channel. Typical optoelectronic noise models have been employed to characterize the response of the detection chain down to the digitized return value for each spectral channel [4]. Finally, a decoding algorithm is implemented to extract the unique code from a satellite passage, based on the interrogation of the spectral channels compliant to the code family.

In the TNO-SLP concept each tag consists of an array of retroreflectors characterized by a binary spectral response (on-off). Due to resolution limitation of typical OGS telescopes, it is not possible to resolve the single retroreflector element. However, the overall return on each spectral channel will be dependent on the amount of active retroreflectors for that channel. This is the basis of the coding mechanism of TNO-SLP. In the decoding phase, all spectral measurements are combined and the actual code is extracted based on a maximum-likelihood approach. Since an absolute radiometric measurement for all channel is not possible, the spectral channels must be measured in a relative way. For this a control retroreflector needs also to be integrated in the tag. This element is responsive for all spectral channels considered. Given a total number of retroreflector array $N_{RR} + 1$, with N_{RR} the number of elements that can be allocated to the code, and the total number of spectral channels employed, N_{CH}, the total number of unique combinations can be found as [5]

$$Q_{COMB} = \binom{N_{RR} + N_{CH} - 1}{N_{RR}} \qquad (1)$$

The simulation model has been run on a typical situation involving a low-Earth orbit (LEO) satellite, passing over the TNO OGS, located in The Hague, the Netherlands. The main parameters, considered for the simulation, are tabulated in Table 1. In performing the simulations the input parameters have been set to typical values of available technologies and representative of the simulated scenario. The only deviation is respective to the laser repetition rate, which was limited to sub-kHz values for computational purposes, while typical pulsed lasers in the sub-mJ range can typically achieve repetition rate of tens of kHz.

Table 1. Main parameters considered in the TNO-SLP end-to-end model.

Parameter	**Value**	**Unit**	**Comment**
Tag Number Retroreflectors	4(+1)	(-)	
Tag Spectral Channels	4	(-)	
Tag Spectral Bandwidth	1535-1580	(nm)	
Tag Retroreflector Aperture Diameter	12.7	(mm)	
Satellite Altitude	500	(km)	circular orbit
Satellite Inclination	82.9	(deg)	
Transmitter Laser Pulse Energy	70	(μJ)	
Transmitter Laser Pulse Width	100	(ns)	
Transmitter Laser Pulse Rate	100	(Hz)	comput. limited
Transmitter Beam Half-angle divergence	70	(μrad)	
Receiver Effective Aperture	0.42	(m^2)	

With 4 spectral channels and 4 available slots, a total of 35 unique combinations is possible. The end-to-end simulation has been run over all these possible tags. The simulation reported that for a single passage the tag, mounted on the faces of a satellite, assumed for simplicity to have a box-shape, is visible for $> 45s$. Running the full model, it has been observed that even in presence of stochastic disturbances (mechanical and atmospheric perturbations, optoelectronic noise), 34 tags out of the set of 35 could be potentially decoded with a single passage. While these are preliminary results, the simulation run suggests that the identification concept is feasible and the end-to-end model will be employed as an analysis verification tool for the following phases of the project, when the final OGS system will be designed.

3. GROUND-TO-GROUND TESTS

As a proof-of-principle of the method, a ground-to-ground test has been performed at TNO facilities. This test has been run using available hardware from separate tests on optical free space quantum communication, which run in parallel. Running the test on a shared fa-

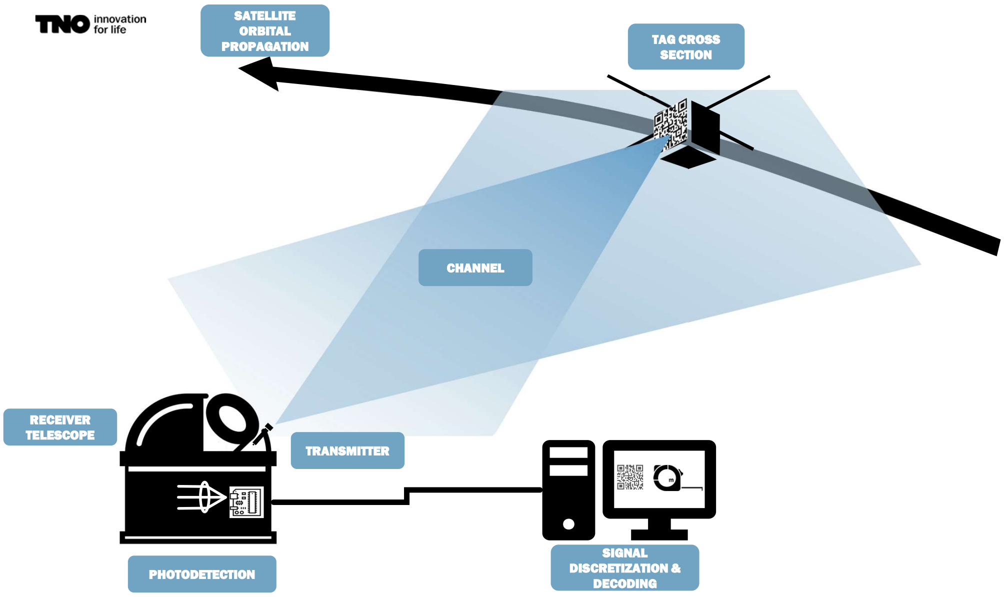

Figure 1. Artist impression of the physical model blocks employed in the SLP end-to-end model.

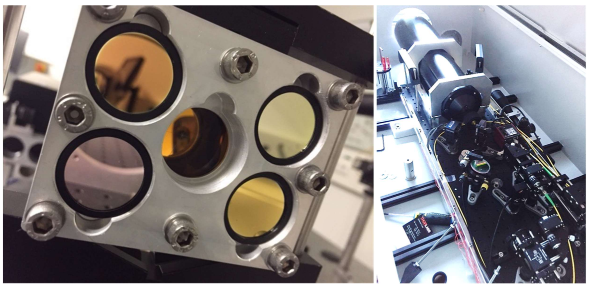

Figure 2. Ground-to-ground test: target tag (left) and transmitter-receiver optical setup (right).

cility could be initially interpreted as a limitation in performance of the system, but actually it demonstrates the maturity of the concept in terms of technology. In fact, all building blocks are already available in the field of optical free space communication. This is very important because it also shows how the TNO-SLP method here proposed can be easily integrated in existing OGS, mainly used for optical communication or laser ranging.
The tests have been conducted over a free space path of 150 m, in between two laboratory spaces located at TNO and TU Delft, in Delft, the Netherlands. The goal of the test was to verify the initial assumptions on photon budget and to demonstrate the feasibility of the tag code reconstruction. For this reason, a simplified test setup has been employed. This consists of a monostatic optical breadboard acting as transmitter and receiver, Figure 2.

The transmitter is composed of a tunable laser, Thorlabs TLX1, modulated by an external modulator, iXblue MX-LN-10, to pulse with 100 ns pulse width and 20 kHz repetition rate. The modulated laser is amplified by an Erbium-Doped Fiber Amplifier (EDFA), Amonics AEDFA-DWDM-20-B-FA, up to an average power of 10 mW. The laser light emitted from the output fiber of the EDFA is collimated with a off-the-shelf collimator, Thorlabs AL2550J-C. After being routed through a series of free space components the collimated beam is magnified by a x10 Galilean refractive afocal telescope, Special Optics custom design, before being launched toaward the tag target.
The same telescope is used for the collection of the return signal (aperture diameter 130 mm). The collected light is routed on a path which is partially shared with the transmitter. The separation between the two paths is implemented by a polarization beam splitter, in a polarization isolation fashion. The collected light is focused by a focusing lens, Thorlabs LA4380-C, onto a quad cell position photodetector, Thorlabs PDQ30C, of which the sum signal line is used to detect the receive signal. The analog signal is acquired by means of an oscilloscope, Rigol DS40334.
For this test, only two spectral channels were employed, 1540 nm and 1560 nm. The tag contains 5 slots, of which 4 could be allocated for the code. This gives a total of 5 combinations possible. For quick identification, the code could be identified with two digits, N_1N_2, representing the number of active slots per channel. In this case, the dictionary of codes is $N_1N_2 \in \{40, 13, 22, 31, 04\}$. To assess the capability of the system to reconstruct the code, all the configurations have been tested and compared with the expected results. The current system does not foresees any spectral multiplexing of the interrogation sig-

nals. This forces the interrogation procedure to be sequential. At the moment of writing this contribution, the results are still under analyses and their outcome will be presented at the conference. At the same time, the optical setup is in an upgrade phase, which will make it suitable for a 2.5 km free space test to be conducted around spring 2023. The upgrade involves mainly the implementation of a multiplexing scheme, in the transmission and receiving mode. This will allow to remove uncertainties over time fluctuations in the propagation channel which are currently negatively affecting the results.

4. CONCLUSION AND OUTLOOK

In this contribution, the TNO-SLP, a cooperative satellite identification method based on an optical spectral coding-decoding scheme, is presented. This method employs passive and minimally invasive retroreflector tags to be mounted on launched satellite. An end-to-end model of the signal propagation and of the tag decoding has been presented. This model has been used to assess the preliminary feasibility of the concept, employing already available technologies. The study has been performed assuming an operation within the C+L band of the optical spectrum, favoring a possible sharing of optical facilities with current OGS employed for optical satellite communication. First proof-of-principle tests have been conducted over a 150 m free space optical link at TNO-TUDelft premises. These tests aimed to show the code reconstruction and to validate initial assumptions on the photon budget and signal recovery. Test results are still under post-processing analyses, but they will be shown at the conference. As outlook on the future activities, it can be mentioned the execution of the test on a longer path with an upgraded optical system, to circumvent some limitations of the previous test. In addition to this, one of the main focus for the future months will be the system design of the transmitter and receiver optics to be installed on the TNO OGS, aiming for a an in-orbit demonstration of the concept.

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