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SPACE SURVEILLANCE NETWORK CAPABILITIES EVALUATION MISSION

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ABSTRACT

The last years saw the diffusion of nano-, pico- and femto-satellite missions thanks to the launch cost reduction and the miniaturization of electronics. Such missions usually present limited capabilities in terms of precise orbit determination and extremely small radar and optical cross-sections. Being they at the edge of ground detection capabilities and not providing independent orbit determination means, their position uncertainty could be quite significant, leading to an increased orbit collisions risk. With this paper, we present a dedicated small satellite mission, composed by multiple nano-, pico- and femto-satellites to evaluate space surveillance networks tracking capabilities and limits, starting from a 3U CubeSat to be deployed as part of a rideshare launch. The satellite, once at a lower orbit, will release smaller sub-satellites equipped with additional tracking systems, including a Global Navigation Satellite System (GNSS) receiver, a set of multiple laser retro-reflectors and Light Emitting Diodes (LEDs) for optical, laser and radar tracking, allowing to characterize also different instruments in terms of capabilities. Sub-satellite separation is implemented upon command to ensure the process can be followed and executed at lower altitudes to limit the orbital lifetime of eventually hard to track small objects that could worsen the space debris problem. Ground characterization (in terms of optical and radar properties) will be performed, also including polarimetric measurements used to identify the separate satellites. All these technologies together will contribute to create a unique tool to estimate the tracking capabilities of multiple instruments, in particular tailored for very small objects, the hardest to track.

Keywords: CubeSat, Space Situational Awareness, Demonstrator, Tracking.

1. INTRODUCTION

The last years saw the diffusion of nano-, pico- and femto-satellite missions thanks to the launch cost reduction and the miniaturization of electronics. Such missions usually present limited capabilities in terms of precise orbit determination and moreover feature extremely small radar and optical cross-sections. Small satellites also tend to be launched in rideshare missions were several tens to a hundred satellites are deployed almost at the same time, making them often challenging to detect and identify. Very rarely these missions carry one or more laser retro-reflectors for precise orbit determination or a miniaturized Global Navigation Satellite System (GNSS) receiver: their usage is also limited because precise orbit determination is rarely a mission requirement and the accuracy achievable with Two Line Elements (TLEs) is usually sufficient.

Being these very small satellites at the edge of the current detection capabilities (both using radar and optical systems) and not providing independent orbit determination means, their position uncertainty could be quite significant, leading to an increased orbit collision risk, especially in the late mission phases when space traffic has to be considered. Tracking performances also show lower accuracies for small objects due to poor disturbances modelling and reduced measurement signal-to-noise ratios, making the picture even darker.

With this paper we present a dedicated small satellite formation, made by multiple nano-, pico- and femto-satellites to evaluate the space surveillance network tracking capabilities and limits: this will be achieved by launching a single spacecraft that is, itself, composed by smaller sub-satellites. By providing each one with independent tracking capabilities, we aim at simulating the debris formation process while also provide precise tracking to verify the performances of the breakup detection systems and, more in general, the tracking performances of current Space Situational Awareness (SSA) monitoring systems. This includes radars, but also telescopes and laser tracking systems on the ground together with on-board solutions such as GNSS receivers, active light emission systems using Light Emitting Diodes (LEDs) and engineered optical coatings to boost satellite visibility.

This paper presents an overview of existing sensors in Section 2, focusing specifically on aspects and systems relevant for small satellites. Section 3 presents some results on the current tracking accuracy, based on publicly

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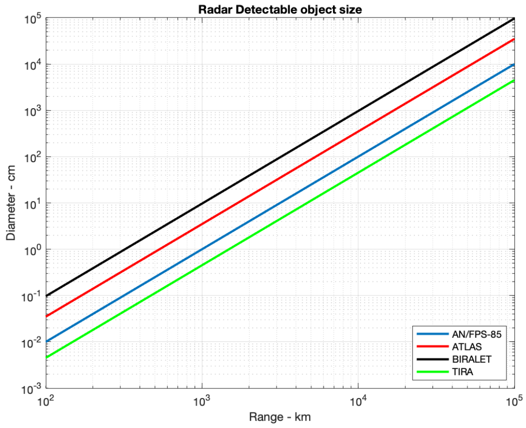

Figure 1. Space surveillance radar performances (based on data from [1] and [2]).

available measurements, on very small satellites. Past and current missions relevant to assess the limits of current space tracking systems are presented in Section 4. Finally, the proposed demonstration mission is presented in Section 5 before final conclusions are drawn in Section 6.

2. TRACKING SENSORS

This section focuses on the different sensors used for tracking space objects and precisely retrieving their orbital elements, presenting relevant aspects for the demonstration mission object of this paper.

2.1. Radar

Radar tracking of space objects is the most common method to obtain orbital elements: many such radars are in use for SSA[1] and they automatically generate orbital elements for all the objects that cross their beam. The minimum object size that can be detected depends on the system hardware (in terms of maximum transmit power and antenna parameters) and the fourth power of the object distance, as shown in Figure 1. This means that very small objects can be detected at short distance and this can be used to infer performances for bigger objects at larger distances.

Orbital elements generated from radar measurements usually suffer from low accuracies due to the very simple nature of the orbital model used and the limited number of measurements[3], showing km-level residuals. Radar tracklets residuals calculated on objects for which precise orbital elements are available (such as those tracked by International Laser Ranging Service (ILRS)) show residuals between few meters and few tens of meters[4].

2.2. Laser

Laser tracking of space objects follows the same principles as radar tracking, where objects crossing a laser fence are detected and their orbital elements calculated. Due to the much smaller beam and higher timing accuracy achievable, orbits can be determined with an accuracy of few centimeters [4] but this requires much more complex dynamic models than the ones used for simple TLEs. Laser tracking [5] is thus fundamental to obtain precise orbital elements that can be used for reference for other instruments and it can often be done by simply monitoring bigger satellite body reflections, while dedicated retro-reflectors are necessary for smaller objects.

Laser tracking could also in principle be used to identify different objects, as presented in [6]: this approach conjugates the advantages of precise laser tracking with identification, based on a set of possible identifiers.

2.3. Optical

Optical observations of satellites are very common and they are usually based on two fundamental principles: the reflection of sunlight directly reflected by the satellite or the direct emission of light from the satellite. The former approach does not require a specific design but it relies on the optical reflection properties of the satellite structure. This can result in intense flares, even from very small satellites[7], but usually such results are not obtained on purpose, making reflections also difficult to predict. Magnitudes up to 0 can be achieved but generally much lower ones are obtained (often below magnitude +7, considered the threshold for naked-eye observation in remote areas [8]). It is important to note that often such reflections can be observed for the full satellite lifetime as degradation of metallic external surfaces is usually limited. The reduced degradation over time makes such flares good for ground observers (as the can be used to track the satellite for the full lifetime) but its magnitude is hardly predictable, making this method not very reliable.

Active light emission from satellites has been already attempted by several missions (such as [8] and [9]) and often small LEDs are controlled to provide a constant or alternating light pattern. Such system allows a much better reproducibility (and eventually identification[9]) but at the cost of on-board power. Due to the LED characteristics and usually limited radiation tolerance, such systems typically have a limited lifetime due to components degradation. Magnitudes just below the visual naked-eye sensitivity have been achieved and for a short lifetime (few months[8]) making such system not ideal for a demonstration mission unless proper component selection is carried out.

Observations are carried out by means of optical sensors with a narrow or broad field of view, with a registration of the right-ascension and declination angle together with precise timing tagging. The information, together with the acquired image of the observed object, can be used to determine the object trajectory up to accuracies in the order of tens of meters at an 800 km altitude [5].

Observations beyond the visual spectrum can also be performed to obtain more information on the external material properties or eventually the satellite object characteristics by including also light spectral and polarization information[10].

2.4. GNSS

GNSS receivers have been used as standard system in space for many years and they are capable to provide precise on-board navigation solutions up to cm-level in Low Earth Orbit (LEO). Such accuracies are not achievable on small satellites, where typical performances vary from meter level to tens of meters, anyway more accurate than TLEs. GNSS receivers on-board small satellites can also be used to generate accurate orbital elements or, in conjunction with a beacon transmitter, to deliver the satellite position in real-time[11]: this solution can be used to provide precise satellite position (within few meters) for validation with respect to other tracking systems, eliminating the orbital fit to TLEs that often increases the position error.

3. TRACKING ACCURACY FOR SMALL OBJECTS

Small objects (being them actual satellites or pieces of debris) are harder to track accurately with respect to bigger objects due to their reduced cross-section: this, in turns, leads to difficulty in detecting the actual object above the background noise[12] or a higher uncertainty in the orbital elements prediction[13] (see Section 2.1 for further details). This is typically expressed as the covariance between successive series of orbital elements[3] and it relates to the position uncertainty of the object, one of the main contributors to the collision risk in space, together with the ever increasing number of objects. It should be noted that, as reported in [3], the covariance underestimates the actual tracking error but this cannot usually be calculated as no alternative method is present (non-collaborative satellite, no alternative precise orbit determination capabilities or debris). Using the methodology described in [13], the launch 2013-066 [14] was considered and the TLE covariance for all the deployed objects has been re-calculated (also to account for improvements in the TLE acquisition and generation system from 2016, when the paper was published) to compare the TLE covariances to the estimated object average cross-section (to also deal with tumbling objects), as shown in Figure 2. It can be clearly noted that the covariance remain relatively constant for objects with a cross-section higher than 0.01m^2, while it increases sharply below such threshold: CubeSats actually were designed to have a 10 cm side exactly for this reason. Smaller objects thus are harder to track and result in degraded performances. Just as a reference, the lowest point in Figure 2, with a cross-section of 0.005 m^2, is equivalent to the object shown in Figure 3, while objects with a cross-section of 0.016m^2 are multiple 1U CubeSats.

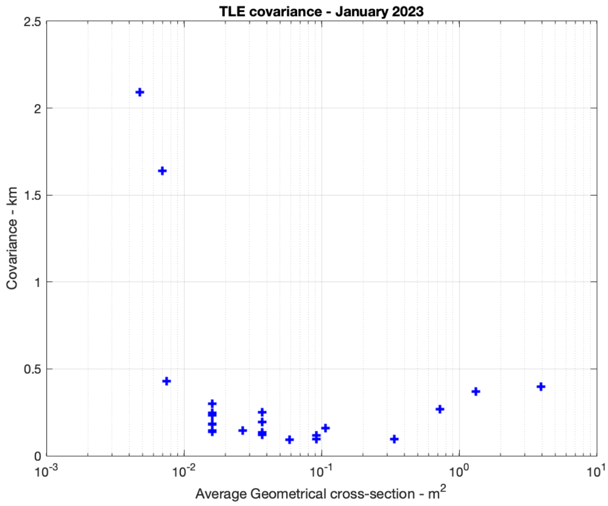

Figure 2. TLE covariance, calculated from objects taken from [13].

It should be also noted that the TLE covariance analysis, when performed on satellites with active orbit control, could lead to unexpectedly high results as this is just the result of continuous orbit adjustments, as it can be noted for the objects with a cross-section higher than 0.5 m^2 in Figure 2.

Very small satellites (relatively speaking, as absolute size and distance are linked to the minimum detectable size by sensors) are thus at the edge of the detection capabilities and are the best objects to characterize performances. It should also be noted that active small satellites can be considered having a size similar to debris generated in

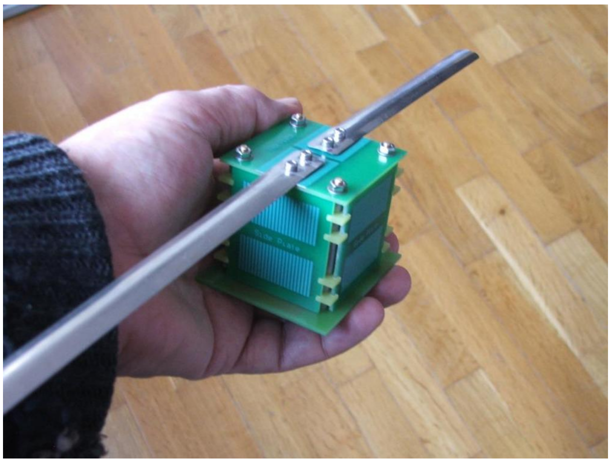

Figure 3. BME-1 [15].

collision or breakup events and, as such, they could help better understanding the debris tracking performances. Having the possibility of generating independent orbital elements (as compared to non-operational satellites or debris) also allows to compare and characterize tracking performances.

4. SMALL CALIBRATION OBJECTS IN SPACE

Small objects are the hardest to detect both by radar and optical instruments because of the reduced signal return, nevertheless they have been used for a very long time as reference for performances evaluation. Some of the first such tests were the Dual and Triple Calibration Sphere experiments, launched respectively in 1964 ad 1971[16]. These experiments used spheres of different diameter (designed to have a constant radar cross-section using the systems in use at the time) launched in a 2800 and 800 km orbit respectively and with diameters varying from 26 to 35 cm. These missions are still orbiting and can be used for radar and visual observations to determine instrument capabilities.

The ODERACS experiment, run by NASA between 1994 and 1996[16] deployed several spheres with a diameter ranging from 5 to 15 cm and dipoles also ranging from 5 to 15 cm in several orbits between 100 and 350 km for radar calibration and performances estimation. All objects decayed by 1996 and cannot be used anymore.

All these objects were fully passive systems and no alternative tracking method was available to compare the precise orbital elements, also due to the size of the different spacecrafts. LARES and LAGEOS missions[17], with a diameter of approximately 36 cm, are still routinely used for laser tracking with orbital residuals of less than a centimeter, making them ideal for calibration.

Active satellites, like the Navstar series [18] or the RADCAL satellite [19] have been used for radar calibration thanks to the availability of accurate orbital elements but their size is relatively big and thus provides limited insights on the performances for small objects. For this aspect, small satellites not specifically developed as radar calibration objects can be used. Satellites as small as 5 cm in side are reported to be trackable at an altitude of 500 km, even if the radar signal return is limited and, possibly, objects require manual interventions from radar analysts for allow for tracking[12]. An extreme case was the deployment of 105 femto-satellites [20] at an altitude of 300 km, each with a size of 3.5 x 3.5 cm. The objects have been deployed on March 19th 2019 and de-orbited within 3 days: they have probably have been tracked, according to the specifications shown in Figure 1, but no orbital element has been publicly released.

5. DEMONSTRATOR MISSION

This section presents a demonstration mission to estimate and compare the detection and orbit determination capabilities of different sensors used for SSA. The mission consists of a main satellite (a 3U CubeSat) that will be deployed using a commercial service to its initial orbit and, at a later stage and after the altitude has decayed to a region with lower traffic, it will deploy smaller objects to test breakup detection in space and minimum size object detection. Each object deployed will be equipped with active tracking means to independently generate orbital elements and to compare those with the detected ones (publicly available TLEs, for example, if the object can be detected). This will allow to better estimate the capabilities of current SSA tracking networks and test, in a controlled environment, the detection of breakups. As multiple objects will be deployed, potential conjunctions (eventually triggered by the use of differential drag on the objects), can be monitored also providing independent measurements to test current algorithms and detection capabilities. As the mission could add to the overall debris risk if small objects are deployed and proved un-trackable, this will be tested in steps also delaying the deployment to ensure minimum lifetime for potentially un-trackable objects.

The next subsections will provide further details into the mission, detailing the different mission goals, components and strategies.

5.1. Mission Goals

The main mission goals can be summarized as follows, also ordered by importance:

1. demonstrate in-space precise tracking of multiple pico- and femto-satellites down to accuracies better than what currently achievable with publicly available TLEs,
2. demonstrate ground tracking (by means of radar, optical and laser tracking) of femto-satellites and assess the achievable orbital elements accuracies,
3. test in-space identification of space objects using laser and optical instruments,
4. provide independent position measurements for two objects involved in a conjunction.

Following from the primary mission goal to track multiple pico- and femto-satellites in space, it was decided to deploy them from a mothercraft to have full control over the deployment process, especially since rideshare launches already deploy up to hundred objects in close proximity and this would have complicated further the mission. Lifetime is also an important goal which has to be traded-off with the risk of deploying small objects in an extremely congested orbit: commercial rideshare programs usually deploy payloads at an altitude of 500 km and this, considering the case of the many CubeSats already deployed at that altitude, provides an orbital lifetime of approximately 3.5 years. Such a full mission duration would allow multiple test opportunities for ground instruments but the deployment of very small objects at that altitude is considered too risky. Lifetime, when the satellite had decayed to an altitude of 300 - 400 km would be less than a year and much less for objects with a low ballistic coefficient (as [20]): this option provides a good compromise for safety and for guaranteeing a long enough period for testing of the ground instruments.

5.2. Mission Description

The mission is based on a mothercraft made by a 3U CubeSat to be deployed using a commercial rideshare service to act as a carrier for all other sub-satellites: this guarantees good control for the deployment and offers a satellite size that has been proved multiple times to be tracked from the ground. Both radar and optical tracking of such satellites have been demonstrated successfully. Optical satellite properties will be analyzed for this mission to also improve visual trackability by means of specific coatings and the mothercraft will also be equipped with a standard set of laser retro-reflectors for satellite tracking and a dedicated "Satellite License Plate"[6] for satellite identification. The main satellite will also carry a GNSS receiver connected to a beacon transmitter to broadcast the satellite position during all the mission phases at regular intervals, to allow to simultaneously track the satellite from the ground and correlate with the actual position, without incurring into extra errors due to the TLE orbit propagation process.

To limit the overall system complexity, the mothercraft is made by two independent sub-satellites, a 1U and a 2U CubeSats docked together and operating, during the first mission phases, as a single satellite. But each sub-satellite is actually fully independent and provided with independent tracking means, in particular with an independent license plate, that would allow to test detection of multiple plates within the same field of view of the ground instrument. This is an important test case in view of using such identification system in a more widespread way. Upon separation of the two main sub-satellites, the whole process can be monitored by using a GNSS receiver on each half of the mothercraft: this will allow to monitor the whole debris generation process and compare the debris generation prediction algorithms.

As mentioned already, optical and laser tracking are important parts of the mission and this will be achieved using instruments in development in The Netherlands located at the Delft University of Technology and TNO, a partner research institute. The separation of the sub-satellites will be timed to be optimally followed with all the instruments and monitored also by other subjects, such as the European Space Situational Tracking network or the American 18th Space Defense Squadron.

Sunlight reflections on the satellite surfaces will be simulated in order to evaluate different coating options to test on the different satellites but active solutions, as already demonstrated by other teams[9], will also be implemented. In previous literature, LEDs on the outside of the satellite have been used to improve the detectability of the satellite shortly after deployment but no references have been found to the use of such solutions in the longer term (and specifically on the survival to radiation degradation after months or years). Due to the specific needs of our mission, it is important to guarantee LEDs remain operational for the full mission to guarantee the satellites can be used for calibration with different ground systems. Radiation protection for the active elements will be an important aspect to analyze.

After the separation of the two halves of the mothercraft, each part will be an independent satellite and will continue its mission: considering a minimal separation velocity between the satellites, their relative distance will increase and it is expected to control it by means of differential drag (and a deployable appendage) such that the two objects could reduce their distance leading to a conjunction. This is a mission goal but, due to the limited control forces on the satellites, the probability of success is considered low: simulating a complete conjunction in between two active satellites could be used to validate conjunction prediction algorithms with in-flight precise data (assuming active on-board GNSS tracking during the conjunction).

As 1U and 2U CubeSats have also been proved already to be successfully trackable, each sub-satellite carries a further smaller spacecraft, down to an expected 3-5 cm size smaller object to be deployed at a lower altitude (as done in [20]). The difference with the previous attempts would be that only one object would be deployed from each satellite, allowing a simple tracking and providing also independent orbital element determination from on-board instruments. It is expected to deploy objects with a higher ballistic coefficient than in [20] such that deorbiting could be not as quick, providing at least few months of testing time.

5.3. Instrument baseline

The space segment of the proposed mission will include passive and active means of satellite tracking and identification, to be coupled to a series of ground instruments. Miniaturized GNSS receivers will be placed on each satellite to transmit regular position reports to the ground: this has already been demonstrated on CubeSats as they provide a higher power generation but it is considered challenging on smaller satellites. Radio transmissions from the satellite (in terms of telemetry beacons or simply an un-modulated carrier) will be used also to determine the satellite orbital parameters and it is expected to lead a solution slightly more accurate than public TLEs. LEDs and satellite coatings will be used instead to maximize the spacecraft visibility and a ”Satellite License Plate” will also be used to identify, in a complete passive way, each satellite.

On the ground, an optical telescope fitted for observations in the visual spectrum will be used for object detection and orbital elements generation together with an experimental system employing full spectro-polarimetric measurements to identify the satellites.

6. CONCLUSIONS

This paper presented an overview of the efforts to track small small space objects, briefly listing the available sensors, in space and on the ground, and estimate the object orbital elements. Such activity is fundamental as small space objects often show worse tracking performances, as also presented here, in terms of position uncertainties growing with the decreasing object size, and ultimately this can lead to extra risks for important space assets. In order to assess current tracking performances, especially for small objects, an overview of the previous calibration objects has been presented, showing very small passive objects have been used. This paper also presented an attempt to improve the SSA networks by assessing their performances with small objects by proposing a satellite formation composed by multiple small objects, deployed sequentially from a mothercraft. This mission is currently under design and aims at estimating the small objects tracking capabilities of different type of instruments, including space surveillance radars, optical telescopes and laser tracking systems. This mission also aims at demonstrating passive optical object identification by means of a ”Satellite License Plate”. Furthermore, the mission also aims at providing precise data to quantify the performances of existing breakup and conjunction detection systems by providing precise tracking of the objects in space.

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