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Long-term performance analysis of NORAD Two-Line Elements for CubeSats and PocketQubes

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Abstract: This paper aims at analysing the current capabilities of the NORAD Space Surveillance network, in particular focusing on very small objects in LEO. Spacecraft miniaturization has been pushing the limits and capabilities of small satellites so much that spacecraft as small as 5x5x5 cm have already been launched and even smaller ones are currently envisaged. A common remark is that these objects would be impossible to track with the available radar sensors and they would ultimately only be a threat to existing and future space assets. By analysing the objects in the NORAD catalog, we demonstrate that similar sized objects are currently tracked successfully. Covariance analysis of the available orbital elements is used to demonstrate orbital elements accuracies similar to bigger satellites. We demonstrate as well that measured cross-section is consistently over-estimated for very small objects equipped with VHF or UHF antennas actually showing that this could boost their radar reflectivity. This paper shows that objects smaller than 10 cm in side are trackable by current surveillance radars and do not pose a higher threat than other satellites, in case proper measures are taken.

1. INTRODUCTION

This paper deals with the space debris problem from the point of view of a spacecraft operator whose interest is the safety of its own space assets or an agency monitoring orbiting objects. In this paper we want to analyse the possible dependence of position errors on satellite size, to highlight eventual issues with small and very small satellites. Orbit knowledge of a spacecraft (and of all the possible objects with potentially close encounters) is of key importance: the orbital elements, including small satellites, are provided by Air Force Space Command through their public catalog [1] as Two-Line Elements (TLE) for those operators which cannot calculate them (by means of on-board GNSS receivers or ranging transponders). The typical accuracy of those elements is a few kilometres, as shown by the analysis of spacecraft equipped with GNSS receivers [2][3][4] or using 2-way ranging. As pico- and femto-satellites typically do not have such equipment due to form factor and power constraints, TLEs are the only option.

Our purpose is to demonstrate that the current surveillance radars capabilities are sufficient to track objects as small as 5 cm in radius, despite the general consensus that the current systems are limited to objects twice as big (~10 cm). Our analysis, being based on data collected on flying spacecraft, will not deal with even smaller satellites being currently proposed [5]. To prove this, we focused on the launch of the Dnepr-19 on Nov 21st, 2013, which is, to date, the only one including, beside some main payloads, PocketQubes (with a size down to 5x5x5 cm) and CubeSats (with a size down to 10x10x10 cm). A total of 31 satellites were launched, of which 4 PocketQubes and 18 CubeSats, with different sizes and masses, and were all deployed in similar orbits, with the perigee ranging from 560 to 600 km and the apogee from 600 to 700 km.

Section 2 describes the satellites used as reference in this paper and Section 3 describes the method used to compare the different satellite sizes. The available TLE sets were analysed for estimating the current update frequency (Section 4) and covariance (Section 5). Radar cross-section was also analysed (Section 6). A recommendation for improving the detectability of very small objects is reported in Section 7.

2. DATA SET DESCRIPTION

Among all the 31 satellites launched on the Dnepr-19, 30 were actually deployed: UNISAT-5 was supposed to deploy 8 spacecraft but one of them was not released upon customer's request [6]. Table 1 shows more details about those satellites. The object (Dove 4) was assigned a NORAD ID (39434) even if it was not physically deployed. The satellite was designed and produced by Planet [7] and by looking at the measured radar cross-section (0.02 m^2) [8] it can be seen that the number is significantly smaller

Name	Norad ID	Size [cm]	Mass [kg]	Notes
WREN	39434	5x5x5	0.25	1P PocketQube (deployed from UNISAT-5)
50$Sat	39436	5x5x7.5	0.21	1.5P PocketQube (deployed from UNISAT-5)
BeakerSat-1	39437	5x5x12.5	0.4	2.5P PocketQube (deployed from UNISAT-5)
QubeScout-S1	39443	5x5x12.5	0.4	2.5P PocketQube (deployed from UNISAT-5)
FUNcube 1	39444	10x10x11.4	1.0	1U CubeSat
ZACube-1	39417	10x10x11.4	1.0	1U CubeSat
UWE-3	39446	10x10x11.4	1.0	1U CubeSat
HINCUBE	39445	10x10x11.4	1.0	1U CubeSat
NEE 02	39441	10x10x11.4	1.0	1U CubeSat with deployable solar panels
FIRST-MOVE	39439	10x10x11.4	1.0	1U CubeSat
VELOX-P2	39438	10x10x11.4	1.0	1U CubeSat
HUMSAT D	39433	10x10x11.4	1.0	1U CubeSat (deployed from UNISAT-5)
ICECUBE 1	39432	10x10x11.4	1.0	1U CubeSat (deployed from UNISAT-5)
PUCP-SAT 1	39442	10x10x11.4	1.0	1U CubeSat (deployed from UNISAT-5)
GOMX 1	39430	10x10x22.8	2.0	2U CubeSat
CubeBUG 2	39440	10x10x22.8	2.0	2U CubeSat
Triton 1	39427	10x10x34.2	3.0	3U CubeSat
OPTOS	39420	10x10x34.2	3.0	3U CubeSat
Delfi-N3xt	39428	10x10x34.2	3.0	3U CubeSat with deployable solar panels
DOVE 3	39429	10x10x34.2	5.2	3U CubeSat with deployable solar panels
CINEMA 2	39424	10x10x34.2	4.0	3U CubeSat with 1m long deployable magnetometer
CINEMA 3	39426	10x10x34.2	4.0	3U CubeSat with 1m long deployable magnetometer
BRITE-PL	39431	20x20x20	10.0	
AprizeSat 7	39416	25x25x25	12.0	
AprizeSat 8	39425	25x25x25	12.0	
WNISAT 1	39423	27x27x27	10.0	
UNISAT-5	39425	46x46x52	28.0	Used to deploy 7 satellites
SkySat 1	39418	60x60x95	83.0	Deployable antenna
STSAT 3	39422	100x100x85	150.0	2x deployable solar panels
DubaiSat-2	39419	150x150x195	300.0	4x deployable solar panels

Table 1: Dnepr-19 satellites[9]

than that of Dove 3 (0.05 m^2), which is completely identical [9]. The same difference is noticed with the following satellites from Planet (FLOCK-1 family, with a radar cross-section ranging from 0.048 m^2 to 0.12 m^2). Based on this consideration and on the fact that the radar cross section for the object 39435 (in the NORAD catalog assigned to WREN) is 0.2499 m^2, clearly not compatible with an object 5x5x5 cm in size, it was assumed that the object 39434 was wrongly assigned to Dove 4, while it should have been assigned to WREN.

3. SATELLITE SIZE COMPARISON

Throughout the paper, we will compare different parameters as a function of the satellite size to try and highlight eventual trends. To properly do this, we used the satellite dimensions listed in Section 2 to calculated an approximated geometrical cross-section. A full 3D model is not available for all satellites to take into account the exact shape so these results will be approximated but will provide an intuitive and qualitative metric for comparison. The geometric cross-section has been calculated by approximating every object with a cuboid (discarding eventual deployable appendixes such as solar panels) and then rotating it over all possible orientations to calculate the maximum, minimum and average geometric cross-section. Materials and electromagnetic interactions have not been considered deliberately. This metric will be used in the following sections to compare different features and highlight eventual trends as a function of satellite size.

4. ORBITAL ELEMENTS UPDATE RATE

Given the simplified nature of the orbital model used with TLEs [4], up-to-date data is fundamental. Several papers focused on the increase of the position error as a function of TLE age [3][4][10]. Our purpose here is to evaluate if the update rate for very small objects could be an issue for successful tracking. Celestrak [9], one of the available public TLE repositories, clearly explains the update strategy as "as-needed basis" and this depends on a number of factors like orbit, possible collision risks, etc. From the point of view on a satellite operator or an agency monitoring orbiting objects, TLE update rate needs to be frequent enough to guarantee proper tracking of the object to limit the propagation error on satellite position. Small size objects could lead to a lower detection probability by a RADAR, actually requiring more samples to be acquired and so leading to a longer averaging time. To ensure this is not the case, the TLE update rate has been calculated for all the objects deployed on the Dnepr-19 launch for their complete lifetime. Figure 1 shows the calculated number of updates per day (only few satellites are shown for the sake of clearness). From the picture, it is clearly visible that several TLEs per day are generated for all the satellites.

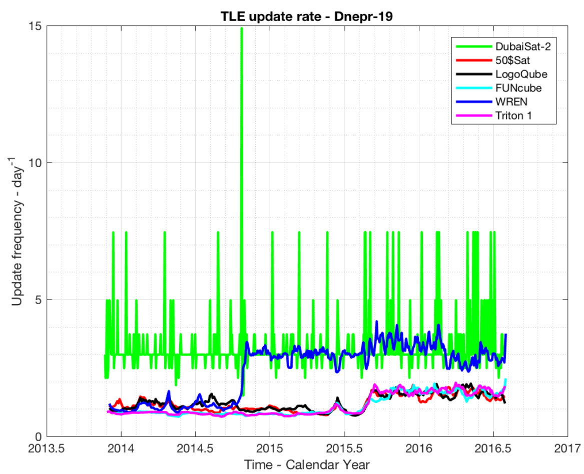

Figure 1: TLE update rate between Nov 21st 2013 and August 1st 2016

This confirms that the TLE update rate would not be a problem for successfully tracking objects as small as 5x5x5 cm in a 600 km circular orbit.

5. TLE SELF-CONSISTENCY

TLE self-consistency [2][10] is a technique used to analyse the errors in orbital elements and their propagation using a set of successive TLEs. This technique proves useful in case no alternative orbital elements are available (such as, for example, an on-board GNSS receiver or a ranging transponder) but, because of that, it suffers from the impossibility to determine the bias error. The result of this analysis shows the error (as a distance) between the position propagated with two consecutive TLEs at the time of release of the second TLE. The update rate of the orbital elements plays an important role in defining the error (that grows over time), so frequent updates help limiting it. The second important component is the accuracy in determining the position of each object, that may be related to its size. In this paper we did not normalize the covariance to the update rate to evaluate the true error, given the available TLEs. The self-consistency analysis is visible in Figure 2, where the covariance is shown (average, variance and maximum) for a period of 31 days (July 2016). The figures show all the satellites in the launch and their average geometrical cross-section (as computed in Section 3) is used on the x-axis to order them for size. Some satellites have been highlighted in the figure, in particular 4 PocketQubes (with sizes ranging from 5x5x5 cm to 5x5x12.5 cm), several CubeSats (with sizes ranging from 10x10x11.4 cm to 10x10x34 cm) and DubaiSat-2 (1.5x1.5x1.95 m) [11]. The figure clearly shows a dependence of the covariance on satellite size, showing that objects smaller than CubeSats (and so than ~10 cm) suffer from additional position errors.

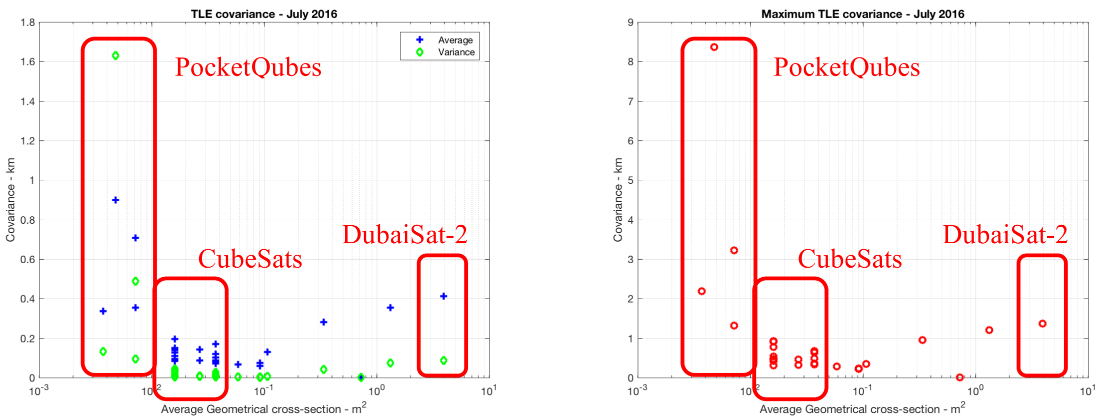

Figure 2: TLE covariance analysis for July 2016. Left picture shows the mean and variance of the covariance, while the right picture shows the maximum values for all the satellites in the Nov 21st 2013 launch.

6. RADAR CROSS-SECTION ANALYSIS

Since TLEs are normally generated from radar measurements of satellite position, it is also of particular interest to look at the radar tracking performances. Taking data from Celestrak [9], the measured Radar Cross-Sections (RCS) were compared with the geometrical size (and all possible orientations) of the satellites. The radar cross-section measures the equivalent area made by a perfect reflector perpendicular to the radar beam reflecting the same amount of energy as the satellite. This takes into account several factors, like the shape and size of the object, its material and also its orientation.

Figure 3 shows the measured radar cross-section compared to the maximum, minimum and average geometric cross-section of the objects (as described in Section 3). RCS measures in figure have been divided into three categories depending on the type of antenna used on the satellite. Satellites using low frequency bands like VHF (around 145 MHz) and / or UHF (around 435 MHz) consistently show a radar cross-section bigger than the expected geometric cross-section, while satellites employing higher frequencies do not show this effect.

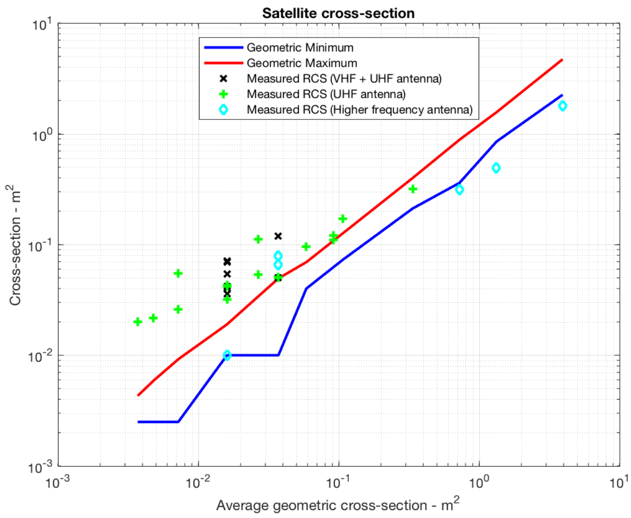

Figure 3: Radar cross section compared to geometrical size.

This can be explained by the interaction of the antenna with the radar beam and by the antenna size. Very small satellites (like CubeSats and smaller) are usually equipped with low gain, omnidirectional wire- antennas made by long metal wires (usually about 50 cm for VHF antennas or approximately 15 cm for UHF antennas). These sticks happen to be of similar or greater size than the satellite, actually strongly influencing the radar cross-section measurement. The effect is limited on bigger satellites due to the structure size as it can be clearly seen in figure. Small satellites using high frequency links rely on very small antennas (patch or similar) that do not influence the measurement as it can be seen in figure. The only two exceptions to this empirical rule can be seen in the centre of the figure: CINEMA 2 and 3 [12], two 3U CubeSats employing a 1 m deployable boom that clearly boosts the radar cross-section.

7. CONCLUSIONS

In this paper, we analysed the available TLEs for objects down to 5 cm in size in the NORAD catalog to estimate the eventual orbital errors and we compared them with bigger satellites to assess an eventual size dependence. We focused on the Dnepr launch on Nov 21st 2013 because it is at the current time the only one including such small objects. TLE update frequency has been analysed since it is of vital importance for satellite operators: from our analysis, we show that the orbital elements of these small objects are updated several times a day, as it happens for much bigger satellites. Due to the lack of alternative methods to estimate the position error, we calculated also the TLE covariance that clearly showed a dependence on satellite size. The maximum covariance increases by a factor 8x for objects of 5 cm size with respect to 10 cm ones. By analysing the available radar cross-section data, we also showed an increase of radar cross-section correlated to the antenna type used on the satellite. The effect is more pronounced for very small satellites and low frequency antennas.
This analysis shows that a low frequency antenna helps in improving the detectability of the object and such an antenna (or similar measures) is strongly recommended for very small satellites to improve their detectability.

8. ACKNOWLEDGEMENT

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