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CRITICALITY ASSESSMENT OF THE ITALIAN NON-MANEUVERABLE SATELLITES IN LOW EARTH ORBIT

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ABSTRACT

Looking at the situation in low Earth orbit (LEO), i.e. below 2000 km, on September 9, 2017, there were 21 Italian satellites, one spent upper stage, crossing most of the region, and one debris related to the OptSat 3000 classified mission, probably a mission related object (MRO). They represented just 0.18% of the objects cataloged in LEO by the US Space Surveillance Network (SSN). Moreover, since the release, in 2002, of the first version of the Mitigation Guidelines compiled by the Inter-Agency Space Debris Coordination Committee (IADC), there had been a significant improvement in the level of compliance with debris mitigation requirements for the Italian satellites, included the so called "25-year" rule, i.e. the limitation of the post-mission disposal lifetime to less than 25 years. Several objects had been, however, launched before the introduction of the IADC Mitigation Guidelines, and also before the more than doubling of the debris population below 1000 km caused, in 2007, by the Fengyun 1C anti-satellite test and, in 2009, by the accidental collision between Iridium 33 and Cosmos 2251.

In this paper, the environmental criticality of the Italian satellites in LEO, from the orbital debris point of view, was evaluated addressing the following issues:

- Their residual lifetime;
- The probability of impact with other objects;
- The probability of catastrophic fragmentation;
- The number of expected fragments in case of catastrophic collisional breakups;
- The possible interference with the orbit of the International Space Station;
- An overall ranking, using a criticality index developed by the authors.

The results obtained not only represented an updated assessment for the Italian objects launched until the summer of 2017, but also a guide for planning and conducting future missions in LEO in a way as safe and sensible as possible.

1. THE ITALIAN SPACE OBJECTS IN LEO

The Italian objects in LEO, on September 9, 2017, are listed in Table 1. The six oldest, from the IRIS rocket stage to the Unisat 2 satellite, were placed in space before the first release of the IADC Space Debris Mitigation Guidelines [1], the following 17 afterwards. Among the latter, the four spacecraft belonging to the COSMO-SkyMed constellation were capable to carry out collision avoidance maneuvers, if needed, and substantial orbit changes with their propulsion system. Instead, it was not clear if the same applied to the recently launched OptSat 3000, a classified reconnaissance spacecraft. Concerning the 3U cubesat D-Sat, it was designed to perform a controlled end-of-life de-orbit burn and reentry a few months after launch, occurred in June 2017, while for Ursa Maior, another 3U cubesat launched together with D-Sat, the deployment of a drag sail was rather planned to induce an accelerated, but uncontrolled, orbital decay.

Table 1

Italian objects in LEO, as of September 9, 2017

US SSN catalog number	Object	Mass (kg)	Altitude (km)	Inclination (°)
22196	IRIS stage	256	278 × 2862	41.15
22783	Temisat	42	934 × 967	82.55
22828	Itamsat	12.5	782 × 797	98.81
26546	Megsat 1	55	581 × 611	64.55
26547	Unisat	12	573 × 624	64.55
27608	Unisat 2	12	619 × 653	64.56
28373	Unisat 3	12	692 × 789	98.34
31135	AGILE	352	467 × 485	2.47
31598	COSMO-SkyMed 1*	1700	621 × 624	97.89
32376	COSMO-SkyMed 2*	1700	621 × 624	97.89
33412	COSMO-SkyMed 3*	1700	621 × 624	97.89
37216	COSMO-SkyMed 4*	1700	621 × 624	97.89
37788	Edusat	10	632 × 686	98.26
38077	LARES	386.8	1436 × 1452	69.49
38078	ALMASat 1	12.5	285 × 694	69.44
39421	Unisat 5	28	585 × 627	97.64
40012	Unisat 6	26	608 × 691	97.84
41459	E-ST@R-2	1.33	436 × 678	98.18
42776	Ursa Maior*	4	496 × 515	97.44
42778	Max Valier Sat	16	496 × 513	97.44
42794	D-Sat♦	4	496 × 509	97.44
42900	OptSat 3000*(?)	368	440 × 461	97.22
42931	2017-044D	?	437 × 459	97.22

* Operational spacecraft with orbital change capability.

♦ The main goal of the mission was the test of a controlled de-orbiting architecture, but on October 3 the satellite was instead placed into a higher 507 × 684 km orbit, with a residual lifetime of 15.4 years.

2. RESIDUAL LIFETIME ESTIMATION

The residual lifetime of the non-maneuverable objects, if < 100 years, was evaluated with the NASA Debris Assessment Software (DAS) utility [2], using the solar flux predictions issued on August 14, 2017. Lifetimes exceeding one century were instead estimated by rescaling the results presented in [3]. Concerning the average tumbling area-to-mass ratios (*A*/*M*), the values adopted are listed in Table 2 [3]. For the mission related object 2017-044D, whose mass, size and shape were unknown, and for which no unclassified Two-Line Elements (TLE) set had been released by the US Strategic Command, a reasonable range of *A*/*M* values was considered. With these assumptions, the residual lifetimes listed in Table 2 were obtained.

Table 2

Average tumbling area-to-mass ratios and residual lifetimes for the non-maneuverable Italian objects in LEO

Object	Area-to-mass ratio (m^2/kg)	Residual lifetime since 2017.7 (years)
IRIS stage	0.01172	7.4
Temisat	0.00438	~3000
Itamsat	0.00648	~380
Megsat 1	0.00656	24.7
Unisat	0.01075	15.7
Unisat 2	0.01075	26.0
Unisat 3	0.01075	83.4
AGILE	0.00682	5.2
Edusat	0.01320	26.6
LARES	0.00027	~500 000
ALMASat 1	0.01560	1.4
Unisat 5	0.03125	6.0
Unisat 6	0.03125	8.7
E-ST@R-2	0.01128	5.9
Max Valier Sat	0.00906	5.5
2017-044D	0.1 – 0.005	0.6 – 4.9

Three satellites, i.e. Temisat and Itamsat, launched before the release of the IADC Mitigation Guidelines, and LARES, launched afterwards, were characterized by extremely long residual lifetimes. Eight objects (50%) resulted to have a residual lifetime < 10 years, 10 (63%) < 25 years, 12 (75%) < 50 years, and 13 (81%) < 100 years. Aside from the very peculiar case of LARES, a passive sphere covered with corner cube laser retro-reflectors, which will remain operational for a very long time as an important component of space geodesy and fundamental physics experiments, the growing adherence with the IADC Mitigation Guidelines, in particular the "25-year" rule, was evident. It should also be remarked that, about one month after the study reference date, D-Sat failed a planned controlled reentry and was placed instead into a higher orbit (507 × 684 km, with an inclination of 97.63°), with a residual lifetime of 15.4 years (assuming an average tumbling *A*/*M* = 0.00875 m^2/kg).

3. DEBRIS IMPACT EXPECTANCY

The debris impact expectancy for the non-maneuverable Italian objects in LEO, as of September 9, 2017, was evaluated with the NASA ORDEM 3.0 model [4]. The results obtained are detailed in Table 3.

Table 3

Current debris impact expectancy for the non-maneuverable objects

Object	Debris ≥ 1 cm ($year^{-1}$)	Debris ≥ 10 cm ($year^{-1}$)	Debris ≥ 1 m ($year^{-1}$)
IRIS stage	7.5×10^{-5}	4.6×10^{-6}	1.6×10^{-6}
Temisat	4.3×10^{-5}	5.3×10^{-6}	3.5×10^{-6}
Itamsat	2.9×10^{-5}	4.2×10^{-6}	2.8×10^{-6}
Megsat 1	2.2×10^{-5}	4.8×10^{-6}	3.2×10^{-6}
Unisat	9.0×10^{-6}	2.7×10^{-6}	2.1×10^{-6}
Unisat 2	1.1×10^{-5}	2.4×10^{-6}	1.7×10^{-6}
Unisat 3	3.5×10^{-5}	3.7×10^{-6}	2.1×10^{-6}
AGILE	2.1×10^{-5}	4.2×10^{-6}	2.2×10^{-6}
Edusat	1.8×10^{-5}	3.0×10^{-6}	2.0×10^{-6}
LARES	5.5×10^{-6}	2.4×10^{-6}	1.9×10^{-6}
ALMASat 1	8.7×10^{-6}	1.5×10^{-6}	1.0×10^{-6}
Unisat 5	7.1×10^{-5}	1.4×10^{-5}	8.2×10^{-6}
Unisat 6	9.9×10^{-5}	1.0×10^{-5}	5.0×10^{-6}
E-ST@R-2	2.2×10^{-6}	1.3×10^{-6}	1.2×10^{-6}
Max Valier Sat	4.6×10^{-6}	1.8×10^{-6}	1.4×10^{-6}
2017-044D*	8.6×10^{-6}	1.1×10^{-6}	5.3×10^{-7}

* Being the object size unknown, the debris flux, in m^{-2} $year^{-1}$, was herein provided.

Considering the orbital debris ≥ 1 cm, the Unisat 6 satellite presented the highest impact probability (9.9×10^{-5} per year), followed by the IRIS stage, Unisat 5 and Temisat. The lowest value was associated with E-ST@R-2 (2.2×10^{-6} per year), followed by Max Valier Sat and LARES. For debris ≥ 10 cm, Unisat 5 had instead the highest impact probability (1.4×10^{-5} per year), followed by Unisat 6, Temisat and Megsat 1. The lowest value was associated with E-ST@R-2 (1.3×10^{-6} per year), followed by ALMASat 1 and Max Valier Sat. Finally, for debris ≥ 1 m, Unisat 5 presented again the highest impact probability (8.2×10^{-6} per year), followed by Unisat 6, Temisat and Megsat 1. The lowest value was associated with ALMASat 1 (1.0×10^{-6} per year), followed by E-ST@R-2, Max Valier Sat and the IRIS stage.

Globally, the collision probability for the Italian non-maneuverable objects in LEO was quite small: 4.5×10^{-4} per year (of which more than 63% due to Unisat 6, the IRIS stage, Unisat 5 and Temisat) with orbital debris ≥ 1 cm, 6.6×10^{-5} per year (of which approximately 52% due to Unisat 5 and 6, Temisat and Megsat 1) with orbital debris ≥ 10 cm, and 4.0×10^{-5} per year (of which nearly 50% due to Unisat 5 and 6, Temisat and Megsat 1) with orbital debris ≥ 1 m. This corresponded, on average, to a collision every 2200, 15 200 and 25 100 years, respectively.

Regarding the four maneuverable satellites of the COSMO-SkyMed constellation and the OptSat 3000 classified spacecraft, the frequency of conjunctions with debris ≥ 10 cm at < 100 m was instead evaluated and presented in Table 4. These conditions corresponded approximately to a collision probability > 5.7×10^{-4} per conjunction for the COSMO-SkyMed satellites, affecting one generic member of the constellation, on average, every 19-20 months. For OptSat 3000, on the other hand, such close approaches, corresponding to a collision probability > 1.8×10^{-4} per conjunction, resulted to occur much less frequently, i.e. just once, on average, every 29-30 years.

Table 4

Conjunction and collision expectancy for the main operational satellites

Object	**Distance of closest approach < 100 m with debris ≥ 10 cm ($year^{-1}$)**	**Impact expectancy with 1 cm ≤ debris ≤ 10 cm ($year^{-1}$)**
COSMO-SkyMed	0.154 (for each of the four satellites)	1.3×10^{-3} (for each of the four satellites)
OptSat 3000	0.034	4.7×10^{-5}

Concerning the mostly untrackable debris in the 1-10 cm size range, still able to cause significant damages, the impact expectancy resulted to be ~ 0.5% per year for the whole COSMO-SkyMed constellation, but only ~ 0.005% per year for OptSat 3000 (see Table 4).

4. CATASTROPHIC COLLISIONS: PROBABILITIES AND CONSEQUENCES

The probabilities of collisions leading to a catastrophic fragmentation of the Italian non-maneuverable objects in LEO, as of September 9, 2017, were estimated by assuming a critical specific energy threshold of 40 000 J/kg [5], in the center of mass of the colliding couple, and an average collision velocity of 10 km/s [6]. The results obtained, again considering the debris fluxes of the appropriate “projectiles” computed with ORDEM 3.0, are summarized in Table 5.

Unisat 5 and 6, with a yearly catastrophic breakup probability around 0.003%, were again at the top of the list, followed by Unisat 3, Itamsat and Temisat, with a yearly probability around 0.001%. The lowest yearly probability (about 0.0002%) was associated with the passive operational satellite LARES. The detrimental effects on the circumterrestrial environment would however depend on the fragments generated by the potential catastrophic breakups, so the expected number of new debris was estimated as well, according to the NASA standard breakup model [7][8], as shown in the last two columns of Table 5.

Table 5

Catastrophic collision probability for the non-maneuverable Italian objects in LEO and minimum number of expected fragments according to the NASA breakup model

Object	Catastrophic collision probability ($year^{-1}$)	Number of fragments ≥ 1 cm	Number of fragments ≥ 10 cm
IRIS stage	4.7×10^{-6}	16 834	328
Temisat	9.2×10^{-6}	4339	85
Itamsat	9.8×10^{-6}	1749	34
Megsat 1	7.1×10^{-6}	5312	104
Unisat	4.4×10^{-6}	1696	33
Unisat 2	4.7×10^{-6}	1696	33
Unisat 3	1.1×10^{-5}	1696	33
AGILE	4.0×10^{-6}	21 375	417
Edusat	7.3×10^{-6}	1479	29
LARES	2.2×10^{-6}	22 941	447
ALMASat 1	3.4×10^{-6}	1749	34
Unisat 5	2.5×10^{-5}	3202	62
Unisat 6	2.6×10^{-5}	3029	59
E-ST@R-2	2.3×10^{-6}	326	6
Max Valier Sat	2.6×10^{-6}	2104	41

Table 6

Average expected number of new debris produced yearly by a catastrophic collision

Object	Number of new fragments ≥ 1 cm per year	Number of new fragments ≥ 10 cm per year
IRIS stage	0.07912	0.00154
Temisat	0.03992	0.00078
Itamsat	0.01714	0.00033
Megsat 1	0.03772	0.00074
Unisat	0.00746	0.00015
Unisat 2	0.00797	0.00016
Unisat 3	0.01866	0.00036
AGILE	0.08550	0.00167
Edusat	0.01080	0.00021
LARES	0.05047	0.00098
ALMASat 1	0.00595	0.00007
Unisat 5	0.08005	0.00155
Unisat 6	0.07875	0.00153
E-ST@R-2	0.00075	0.00001
Max Valier Sat	0.05470	0.00107

Taking into account these figures, in terms of mean expected number of new collisional debris (Table 6), the most critical objects over the short-term resulted to be AGILE, Unisat 5, the IRIS stage and Unisat 6, with an average rate of production of new collisional fragments around 0.08 per year if ≥ 1 cm, and around 0.0016 per year if ≥ 10 cm. E-ST@R-2, on the other hand, was by far the less critical object. The total catastrophic collision probability for the Italian non-maneuverable objects in LEO was approximately 0.01% per year, with a corresponding average rate of production of new collisional fragments of 0.575 per year if ≥ 1 cm, and 0.0112 per year if ≥ 10 cm.

5. INTERNATIONAL SPACE STATION ORBIT CROSSING

The debris conjunction analysis for the International Space Station (ISS), in nearly circular orbit at an altitude of approximately 400 km and with an inclination of about 52°, is particularly burdened by objects in elliptical orbit with a lower perigee and a higher apogee. This geometry, in fact, may entail two crossings of the ISS altitude on each debris orbit and a not negligible uncertainty of the crossing state vector conditions, due to the fact that the low perigee involves a substantial amount of air drag, typically affected by significant modeling inaccuracies.

As of September 9, 2017, only two Italian objects, the IRIS stage and ALMASat 1, belonged to the category of the ISS altitude crossers. Among these, the IRIS stage was the only one with a residual lifetime encompassing the extended operational lifetime of the space station, running through at least 2024, while ALMASat 1 was predicted to reenter in the atmosphere by the end of 2018. Considering the geometry and the evolution of the orbits, the a priori probability of having IRIS crossing the ISS altitude at less than 25 km from the space station was approximately 6% per year at the end of 2017, growing to about 8% per year in 2024. For ALMASat 1, during the last year in orbit, the a priori probability of a conjunction at less than 25 km from the space station was slightly less, about 5%.

Fortunately, the SSN tracking of the IRIS stage, with an average tumbling cross-section of 3 m^2, was not particularly demanding. ALMASat 1, with an average tumbling cross-section of 0.2 m^2, was much smaller, but anyway well above the lower limit for radar tracking in LEO, corresponding to cross-sections > 0.002-0.008 m^2.

6. LONG-TERM ENVIRONMENTAL CRITICALITY

In order to evaluate the long-term environment criticality of the Italian objects in LEO, the normalized and dimensionless criticality index developed by the authors and described in [9] was applied. The average intact object in LEO, as of mid-2013 [10][11], was used for defining a reference object, with mass M_0 = 934 kg and A/M = 0.012 m^2/kg, placed into a circular sun-synchronous orbit with the following characteristics: altitude h_0 = 800 km and inclination i_0 = 98.5°. The criticality index R_N was then defined as:

$$R_N \equiv \frac{F}{F_0} \cdot \frac{L}{L_0} \cdot \left(\frac{M}{M_0}\right)^{1.75} \cdot \frac{L50_{frag}}{L50_{frag0}} \cdot \frac{1+\sin^8(i)}{1+\sin^8(i_0)} \;, \tag{1}$$

where F and F_0 are the fluxes of debris able to induce a catastrophic fragmentation of the object to be ranked and of the reference one, respectively, M and M_0 their respective dry masses, and i and i_0 their orbital inclinations. L_0 is the lifetime of the reference object, while L is, instead, the lifetime of the same reference object if placed in the orbit of the object to be ranked. $L50_{frag}$ and $L50_{frag0}$, finally, represent the time needed for the decay of 50% of the resulting fragmentation debris ≥ 10 cm, for the object to be ranked and for the reference one, respectively. It should be also pointed out that, in order to avoid of weighting too much, in relative terms, objects with lifetimes much longer than any reasonable temporal horizon for the current modeling, technology and social projections, two additional constraints were applied to Eq. (1):

$$\frac{L}{L_0} \equiv 1 \text{ when } L > L_0 \approx 200 \text{ years, and an upper limit for } L50_{frag} \approx 200 \text{ years.} \tag{2}$$

Table 7 lists the objects for which the criticality index assumed a non-negligible value, i.e. $R_N > 0.001$. It included three non-maneuverable objects and four maneuverable ones.

Table 7

Criticality index for the objects with $R_N > 0.001$

Ranking	**Object**	**Criticality index R_N**
1	LARES	1.767
2	Temisat	0.060
3	COSMO-SkyMed 1*	0.021
3	COSMO-SkyMed 2*	0.021
3	COSMO-SkyMed 3*	0.021
3	COSMO-SkyMed 4*	0.021
7	Itamsat	0.005

* If left in the operational orbit at the end-of-life

The most critical object, and the only one with $R_N > 1$, was LARES, with $R_N = 1.767$. Its criticality index was higher than the combined value of all the other objects taken together, actually accounting for more than 92% of the total for the Italian objects in LEO. Among the non-maneuverable objects, Temisat was the second one, with a criticality index ($R_N = 0.060$) already much smaller than one, followed by Itamsat, with a value ($R_N = 0.005$) smaller by a further order of magnitude. Concerning the four COSMO-SkyMed satellites, it was found that even if left in their operational orbits at the end-of-life, their criticality index would amount to just 0.021, i.e. to a combined total value of 0.084.

In conclusion, the overall criticality index of the Italian objects in LEO was slightly less than 2, i.e. their combined long-term criticality for the environment was equivalent to less than two 1-ton spacecraft abandoned in sun-synchronous orbit at 800 km. And just one satellite, LARES, accounted for most of it, while the COSMO-SkyMed satellites were characterized by a relatively small criticality even in their operational orbits.

7. CONCLUSIONS

The Italian objects in LEO where thoroughly analyzed in order to re-assess their short and long-term impact on the orbital debris environment. Over the years, the degree of compliance with the IADC Mitigation Guidelines improved steadily. Moreover, these objects accounted for only 0.18% of the cataloged objects and 0.28% of the mass in LEO, so their global environmental impact was anyway expected to be modest.

Concerning the 23 objects in orbit as of September 9, 2017, 17 (74%) had a residual lifetime < 25 years, 19 (83%) < 50 years, 20 (87%) < 100 years, and 3 (13%) > 200 years. The total collision expectancy with debris ≥ 10 cm corresponded to an average waiting time between collisions of approximately 15 000 years, while a conjunction at less than 100 m with the OptSat 3000 and the four COSMO-SkyMed satellites was expected, on average, every 18 months. The global probability of a catastrophic collision leading to the complete fragmentation of an Italian object was 0.01% per year, with a corresponding average rate of production of new decimeter-sized fragments of 0.0112 per year.

Among the objects in orbit, only the IRIS stage had the potential to cross the altitude of the International Space Station, twice per orbit, thorough the extended operational lifetime of the human outpost, i.e. up to 2024. Overall, the average probability of having the IRIS stage transiting at less than 25 km from the space station was around 7% per year.

Regarding, finally, the long-term impact on the debris environment, the total criticality of the 23 Italian objects in LEO was roughly equivalent to that of a couple of 1-ton spacecraft abandoned in sun-synchronous orbit at 800 km. However, more than 90% of the criticality was associated with just one satellite, LARES, a passive sphere with an extremely low area-to-mass ratio, placed at an altitude of approximately 1440 km to carry out experiments in fundamental physics and geodesy for an extended period of time.

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