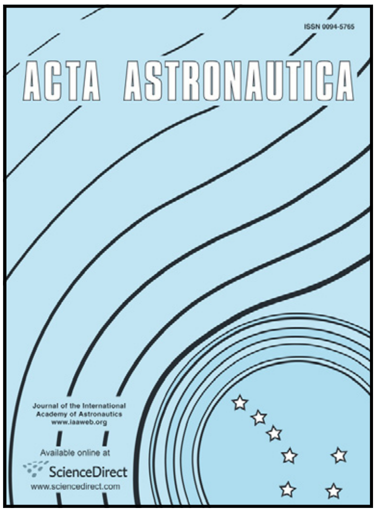

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COMPLIANCE OF THE ITALIAN SATELLITES IN LOW EARTH ORBIT WITH THE END-OF-LIFE DISPOSAL GUIDELINES FOR SPACE DEBRIS MITIGATION AND RANKING OF THEIR LONG-TERM CRITICALITY FOR THE ENVIRONMENT

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As of mid-2014, nearly 50 years since the launch of the first satellite, Italy had placed in low Earth orbit 29 objects: 27 payloads, 1 rocket body and 1 mission related object. 19 were yet in space: the IRIS rocket body and 18 payloads, 4 of which, belonging to the COSMO-SkyMed constellation, still operational and maneuverable. 16 objects had been deployed in space before the approval, in 2002, of the IADC *Space Debris Mitigation Guidelines* and 1 further payload had been launched before the ASI signature of the *European Code of Conduct for Space Debris Mitigation*, in 2005. While no object had been yet maneuvered to reduce its residual lifetime, due to the operational orbits chosen and area-to-mass ratios, 16 of them had decayed or were predicted to reenter in less than 25 years after mission completion, in agreement with current disposal recommendations. This corresponded to a compliance of 64% over 50 years, of 59% for the objects placed in orbit before the ASI signature of the *European Code of Conduct*, and of 75% for those launched afterwards, excluding the 4 maneuverable spacecraft still functional. Concerning the risk on the ground associated with uncontrolled reentries, just one satellite decayed in 2003 had a mass greater than 600 kg and a casualty expectancy in excess of 10^{-4}. For it, timely reentry predictions and alert time windows had been provided to the countries overflown. In order to evaluate the potential long-term detrimental effects on the environment of the abandoned or unmaneuverable objects, a new ranking index, also useful for active debris removal priority listing, was developed and applied. It is worth noting that all the 14 objects residing or descending below 1000 km exhibited an overall ranking index equivalent to just 8% of an average abandoned intact object in a 800 km sun-synchronous orbit.

Keywords: Space Debris, Mitigation, Disposal Guidelines Compliance, Environmental Criticality Ranking, Active Removal.

I. INTRODUCTION

The first Italian satellite, San Marco 1, was launched on 15 December 1964. In the succeeding 50 years, 29 objects were placed in low Earth orbit (LEO), or in orbits crossing LEO (Table 1) [1]: 27 payloads, 1 rocket body and 1 mission related object (MRO). As of mid-2014, 19 of them were still in space (Table 2) [1]: the IRIS rocket body and 18 payloads, 4 of which, belonging to the COSMO-SkyMed constellation, both operational and maneuverable.

The purpose of the analysis presented in this paper was to show how the mission profiles and the orbits chosen in the LEO protected region [2] evolved during a period of time in which international guidelines intended to mitigate the proliferation of orbital debris were progressively elaborated and adopted. In this regard, a few prominent dates should be mentioned:

1. The approval, in 2002, of the *Space Debris Mitigation Guidelines* [2] by the Inter-Agency Space Debris Coordination Committee (IADC), including the Italian Space Agency (ASI);
2. The ASI signature of the *European Code of Conduct for Space Debris Mitigation* [3], in 2005, drafted by the European Space Debris Safety and Mitigation Standard Working Group;
3. The adoption of Resolution A/RES/62/217 [4] by the General Assembly of the United Nations, at the end of 2007, endorsing the *Space Debris Mitigation Guidelines of the Committee on the Peaceful Uses of Outer Space* [5];
4. The approval, in 2010, by the International Organization for Standardization (ISO), of the international standard ISO 24113 [6] (*Space Systems – Space Debris Mitigation Requirements*), prepared by Technical Committee ISO/TC 20, "Aircraft and Space Vehicles", Subcommittee SC 14, "Space Systems and Operations".

Specifically concerning the end-of-life disposal, a wide international consensus coalesced on the following recommendations [2]:

1. «Whenever possible spacecraft or orbital stages that are terminating their operational phases in orbits that pass through the LEO region, or have the potential to interfere with the LEO region, should be de-orbited (direct reentry is preferred) or where appropriate maneuvered into an orbit with a reduced lifetime. Retrieval is also a disposal option.»
2. «A spacecraft or orbital stage should be left in an orbit in which … atmospheric drag will limit the orbital lifetime after completion of operations. … [IADC and other entities] have found 25 years to be reasonable and appropriate.» This prescription became informally known as the "25 years rule".
3. «If a spacecraft or orbital stage is to be disposed of by reentry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk to people or property.»
4. «In the case of a controlled reentry of a spacecraft or orbital stage, the operator of the system should inform the relevant air traffic and maritime traffic authorities of the reentry time and trajectory and the associated ground area.»

Object	Launch date	Reentry
San Marco 1	15 Dec 1964	13 Sep 1965
San Marco 2	26 Apr 1967	14 Dec 1967
San Marco 3	24 Apr 1971	29 Nov 1971
San Marco 4	18 Feb 1974	4 May 1976
San Marco D	25 Mar 1988	6 Dec 1988
IRIS stage	22 Oct 1992	In orbit
IRIS MRO	22 Oct 1992	8 Jan 2005
Temisat	31 Aug 1993	In orbit
Itamsat	26 Sep 1993	In orbit
TSS-1R	22 Feb 1996	19 Mar 1996
BeppoSAX	30 Apr 1996	29 Apr 2003
Megsat	28 Apr 1999	4 Nov 2003
MITA-NINA	15 Jul 2000	15 Aug 2001
Megsat 1	26 Sep 2000	In orbit
Unisat	26 Sep 2000	In orbit
Unisat 2	20 Dec 2002	In orbit
Unisat 3	29 Jun 2004	In orbit
AGILE	23 Apr 2007	In orbit
COSMO-SkyMed 1	8 Jun 2007	In orbit
COSMO-SkyMed 2	9 Dec 2007	In orbit
COSMO-SkyMed 3	25 Oct 2008	In orbit
COSMO-SkyMed 4	6 Nov 2010	In orbit
Edusat	17 Aug 2011	In orbit
LARES	13 Feb 2012	In orbit
ALMASat 1	13 Feb 2012	In orbit
E-ST@R	13 Feb 2012	In orbit
Unicubesat-GG	13 Feb 2012	In orbit
Unisat 5	21 Nov 2013	In orbit
Unisat 6	19 Jun 2014	In orbit

Table 1: Italian objects launched in LEO, as of mid-2014 [1]. The IRIS upper stage and MRO were placed in elliptical orbits crossing LEO of approximately 290 × 5900 km.

II. END-OF-LIFE DISPOSAL PRACTICES IN LEO

For the purposes of this paper, the Italian objects placed so far in LEO can be grouped in four categories: (1) those already decayed from orbit; (2) those abandoned and still in orbit; (3) those still operational, but unable to carry out orbital maneuvers; and (4) those both operational and maneuverable. San Marco 1, the first Italian satellite, belongs to the first category, the IRIS upper stage belongs to the second category, AGILE and LARES are examples of the third one, and the 4 spacecraft of the COSMO-SkyMed constellation are the exclusive members of the fourth one.

Object	Altitude (km)	Inclination (°)
IRIS stage	285×3279	41.15
Temisat	935×967	82.55
Itamsat	784×797	98.65
Megsat 1	597×611	64.56
Unisat	591×625	64.55
Unisat 2	612×669	64.56
Unisat 3	695×792	98.20
AGILE	494×518	2.47
COSMO-SkyMed 1	621×624	97.88
COSMO-SkyMed 2	621×624	97.88
COSMO-SkyMed 3	621×624	97.88
COSMO-SkyMed 4	621×624	97.88
Edusat	637×690	98.20
LARES	1435×1453	69.49
ALMASat 1	304×1145	69.47
E-ST@R	283×790	69.45
Unicubesat-GG	285×826	69.46
Unisat 5	592×636	97.78
Unisat 6	614×699	97.98

Table 2: Italian objects in LEO, as of mid-2014 [1].

In order to verify how the disposal of the Italian satellites in LEO was affected by the introduction of the current international mitigation guidelines, in particular the so-called “25 years rule”, the first three categories were considered. The inclusion of the first two is obvious, while for the disposal of the COSMO-SkyMed spacecraft, belonging to the fourth category, the conclusion of the mission and the outcome of the lifetime reduction de-orbiting had to be waited for. Concerning the satellites belonging to the third category, even if still operational and not ascribable, from the legal and practical point of view, to orbital debris, it was just a matter of time. At mission completion, having no possibility to maneuver for reducing the residual lifetime, the compliance or not with the “25 years rule” would have been an inevitable consequence of the orbit chosen at launch. Moreover, the operational status of micro and nanosatellites not managed by space agencies or institutional operators is often unknown or uncertain. For these reasons, such a category was included as well in the analysis of the compliance with the disposal guidelines.

Table 3 details the mass and the average tumbling cross-section of the abandoned or unmaneuverable Italian objects in LEO belonging to the above mentioned categories (2) and (3). With the exception of AGILE, the average tumbling cross-sections were computed from the published shapes and sizes of the objects under consideration. For AGILE, having not found a reliable source of spacecraft sizes, the average cross-section was estimated by fitting the observed orbital decay due to air drag, during the first half of 2014, with the SATRAP software tool [7].

Object	Mass (kg)	Average tumbling area (m^2)
IRIS stage	256	3
Temisat	42	0.184
Itamsat	12.5	0.081
Megsat 1	55	0.361
Unisat	12	0.129
Unisat 2	12	0.129
Unisat 3	12	0.129
AGILE	352	2.4
Edusat	10	0.132
LARES	386.8	0.104
ALMASat 1	12.5	0.195
E-ST@R	1	0.015
Unicubesat-GG	1	0.019
Unisat 5	28	0.875
Unisat 6	26	0.875

Table 3: Physical characteristics of the abandoned or not maneuverable Italian objects in LEO, as of mid-2014.

In mid-2014, most of the objects listed in Table 3 were abandoned, so their residual lifetime added to the time elapsed since the end of their mission could be used to verify the compliance with the “25 years rule”. Regarding AGILE, LARES and a few of the most recent university microsatellites, still operational, the residual lifetime was estimated as well, but a reasonable guess of the mission duration was subtracted to check the compliance with the disposal recommendations.

The residual lifetime was estimated with STELA, a semi-analytic orbit propagator designed by CNES, the French Space Agency, to support the implementation of the French Space Act [8]. A variable solar activity flux was considered, using the last NASA prediction issued for the DAS software tool (4 September 2013) [9]. The results obtained are summarized in Table 4.

As of mid-2014, no object in LEO had been maneuvered to reduce its residual lifetime, but, due to the operational orbits chosen and area-to-mass ratios, 16 out of 25, i.e. 64%, had decayed or were predicted to reenter in less than 25 years after mission completion, in agreement with current disposal recommendations. Before the approval of the IADC *Space Debris Mitigation Guidelines*, 10 objects out of 16 had been compliant, i.e. 62.5%. This percentage grew to 66.7% (6 out of 9) for the satellites launched afterwards, and to 75% (6 out of 8) for those put in space after the ASI signature of the *European Code of Conduct for Space Debris Mitigation*. Moreover, taking into account that LARES, a completely passive high density sphere covered with corner cube laser retroreflectors, will remain operational for many decades, possibly centuries, for geodetic and fundamental physics research, and that the spacecraft of the COSMO-SkyMed constellation are planned to be de-orbited according to the “25 years rule”, the actual tendential percentage of compliance with the post-disposal lifetime recommendation can be placed in between 80% and 90%.

Object	Post-mission residual lifetime L_T (years)	Compliance with the 25 years rule
San Marco 1	< 1	Yes
San Marco 2	< 1	Yes
San Marco 3	< 1	Yes
San Marco 4	< 1	Yes
San Marco D	< 1	Yes
IRIS stage	$25 < L_T < 50$	No
IRIS MRO	< 13	Yes
Temisat	> 200	No
Itamsat	> 200	No
TSS-1R	< 1	Yes
BeppoSAX	1	Yes
Megsat	< 4	Yes
MITA-NINA	< 1	Yes
Megsat 1	$25 < L_T < 50$	No
Unisat	$25 < L_T < 50$	No
Unisat 2	$25 < L_T < 50$	No
IADC Space Debris Mitigation Guidelines		
Unisat 3	$50 < L_T < 100$	No
European Code of Conduct for Debris Mitigation		
AGILE	< 10	Yes
UN COPUOS Space Debris Mitigation Guidelines		
ISO 24113 Space Debris Mitigation Requirements		
Edusat	$25 < L_T < 50$	No
LARES	> 200	No
ALMASat 1	< 10	Yes
E-ST@R	< 5	Yes
Unicubesat-GG	< 5	Yes
Unisat 5	< 10	Yes
Unisat 6	< 10	Yes

Table 4: Post-mission residual lifetimes of the Italian objects launched in LEO, as of mid-2014. The still operational and maneuverable spacecraft of the COSMO-SkyMed constellation are excluded. The objects are listed in chronological order and the rectangular boxes show when specific mitigation guidelines or standards were approved.

For the Italian objects in LEO, the percentage of compliance with the “25 years rule”, before it was formulated and incorporated in the IADC mitigation guidelines, was therefore already the same (≈63%) inferred from global space activity since 2000 [10]. In other words, *before* the approval of the IADC mitigation guidelines, the Italian objects in LEO displayed the same level of compliance recorded worldwide *after* the approval of the disposal recommendations. And the compliance trend in mid-2014 (>80%) was significantly higher than the global one. Before 2005, a residual lifetime of more than 50 years had occurred 3 times, i.e. in 17.6% of the cases, none of them involving ASI satellites.

Since 2005, after the projects had enough time to adjust to the IADC *Space Debris Mitigation Guidelines* and the ASI signature of the *European Code of Conduct for Space Debris Mitigation*, only one violation of the “25 years rule” has occurred and the 50 years residual lifetime threshold has not and will not be violated by 11 out of 12 satellites (91.7%) launched since then, even in case of spacecraft failure before disposal (e.g. COSMO-SkyMed). Concerning the satellite left out, LARES, taking into account its very peculiar nature, it might remain “functional”, carrying out its intended mission, for a very long time, at least until humankind will decide (or will be forced) to abandon satellite laser ranging. Therefore, LARES will legally become a "debris" only very far in the future, and should be considered, in principle, not compliant in the very long-term, but compliant, from a practical point of view, for at least many decades to come.

III. REENTRY GROUND RISK MANAGEMENT

Concerning the risk on the ground associated with uncontrolled reentries, just one Italian object decayed so far, BeppoSAX in 2003, had a mass greater than 600 kg and a casualty expectancy in excess of 10^{-4}, the alert threshold adopted at the international level. At that time, detailed reentry predictions and alert time windows were provided to all the countries overflown, to the United Nations and to the relevant air and maritime traffic authorities [11][12].

Among the objects presently in orbit, only the four COSMO-SkyMed spacecraft have a mass exceeding 400 kg (~1700 kg at launch) and will probably present a casualty expectancy higher than 10^{-4}. Anyway, their reentry is still many years in the future, the details depending on the outcome of the end-of-life disposal, and plenty of time will be available for comprehensive risk analyses and preparations.

IV. RANKING OBJECTS FOR ENVIRONMENT CRITICALITY AND ACTIVE REMOVAL

The rationale behind the adoption of the "25 years rule" was avoiding the undue accumulation of intact spacecraft and rocket bodies, in which approximately 97% of the mass in LEO is concentrated [13], with the goal of averting the long-term environment instability triggered by mutual collisions and catastrophic breakups [14]. The reverse of the coin of satellite disposal is then represented by the potentially adverse long-term effects on the debris environment of the objects abandoned in LEO after the conclusion of their missions.

A common way to evaluate the latent long-term environmental impact of an orbiting object, refraining from running thousands of complex simulations based on quite uncertain scenario assumptions, is to devise a ranking scheme grounded on reasonable premises [15][16][17][18]. The main advantage of these heuristic approaches is the adoption of simple to understand and simple to apply rules, while the main drawback is the lack of a validated cause-effect foundation, unavoidable if the uncertain, stochastic and possibly chaotic nature of the long-term debris evolution is taken into account. Notwithstanding this limitation, in order to evaluate the long-term detrimental effects of the Italian objects in LEO, we devised a new ranking scheme, further developing and extending an approach we introduced in mid-2013 [13].

IV.I Debris Ranking Scheme for Detrimental Effects

Regarding its potential long-term adverse effects on the debris environment, the ranking *R* of an object in LEO, where a higher ranking value is associated with a higher potential threat, can be obtained as the product of two functions:

$$R = f \cdot g \tag{1}$$

where *f* depends on the probability of catastrophic breakup P_c due to orbital debris collision and on the number of new "projectiles" N_p resulting from the breakup, while *g* characterizes the long-term impact on the environment as a function of the fragments cloud lifetime, volume of space involved and interaction with the pre-existing debris distribution.

Being $F(t)$ the flux of debris able to catastrophically breakup the target object, *A* the average collisional cross-section of the latter and *t* the time, the probability of catastrophic fragmentation is given by:

$$P_c = 1 - e^{-\int F(t)\cdot A\cdot dt} \tag{2}$$

However, being in our case $P_c < 0.1$, Eq. (2) can be rewritten as:

$$P_c \approx \int F(t)\cdot A\cdot dt \tag{3}$$

Unfortunately, the time evolution of $F(t)$ is affected by significant uncertainties [19] and, in any case, the computation of the integral in Eq. (3) for each specific target object would be cumbersome, even assuming very simple laws for $F(t)$ (e.g. linear or exponential growth with a fixed global constant), also because the debris flux leading to a catastrophic fragmentation is a function of the target mass M, orbit inclination and decaying altitude as well. Consequently, the simplifying choice was made of including in the ranking scheme just the current flux $F = F(h,i,M)$ provided by a state-of-the-art debris model at the altitude h and inclination i of the target, giving [13]:

$$P_c \sim F(h,i,M) \cdot A \cdot L_T \tag{4}$$

where L_T is the object residual lifetime, which can be expressed, in terms of the body mass-to-area ratio M/A and "normalized" lifetime function $l(h)$, as:

$$L_T \cong l(h) \cdot \frac{M}{A} \tag{5}$$

Figure 1 shows $L_T(h)$ for an average intact object in LEO [13][14][19], with M_0 = 934 kg and A_0 = 11 m^2, i.e. A_0/M_0 = 0.012 m^2/kg, according to the classical relationship [20]:

$$M = 62.013\, A^{1.13} \tag{6}$$

Eq. (4) can then be written in the following way:

$$P_c \sim F(h,i,M) \cdot l(h) \cdot M \tag{7}$$

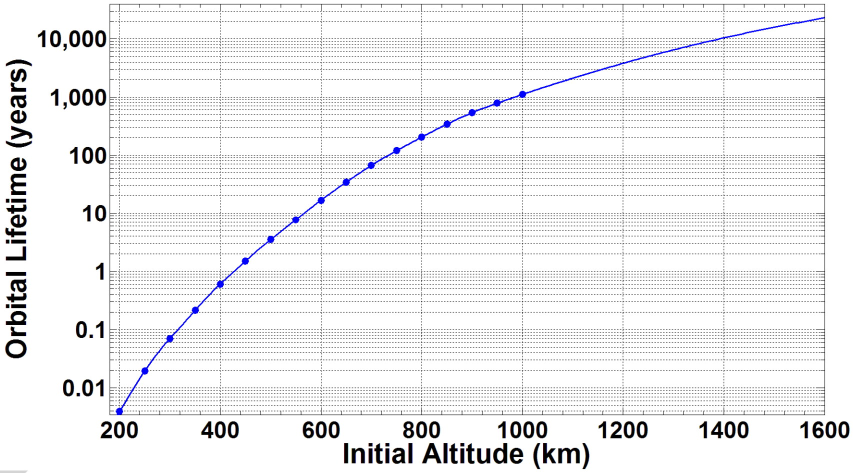

Fig. 1: Mean orbital lifetime, computed as a function of the initial altitude in nearly circular orbit with the SATRAP tool, of an average intact object in LEO, with mass of 934 kg and area-to-mass ratio of 0.012 m^2/kg (reference for the normalization function l).

According to the NASA standard breakup model [21][22], the cumulative number of fragments N_p generated in a catastrophic collision and larger than a given characteristic size is proportional to the cumulative mass of the target object and impacting debris, raised to the 0.75th power. However, the cumulative mass is in practice very close to the target mass, being the latter typically much larger (by 3 orders of magnitude in LEO) than the impactor's one. As a result, $N_p \propto M^{0.75}$, leading to the expression [13][17]:

$$f \equiv F(h,i,M) \cdot l(h) \cdot M^{1.75} \sim P_c \cdot M^{0.75} \tag{8}$$

In order to characterize the long-term impact on the environment of the resulting debris cloud, we introduced the concept of collisional debris cloud decay of 50% of the catalogable fragments (*CDCD*50) [19], with typical size $d \geq$ 10 cm in LEO. Figure 2 shows *CDCD*50, as a function of altitude and solar activity, assuming debris clouds with area-to-mass and velocity distributions similar to those observed following the Fengyun 1C, Cosmos 2251 and Iridium 33 catastrophic breakups [23][24].

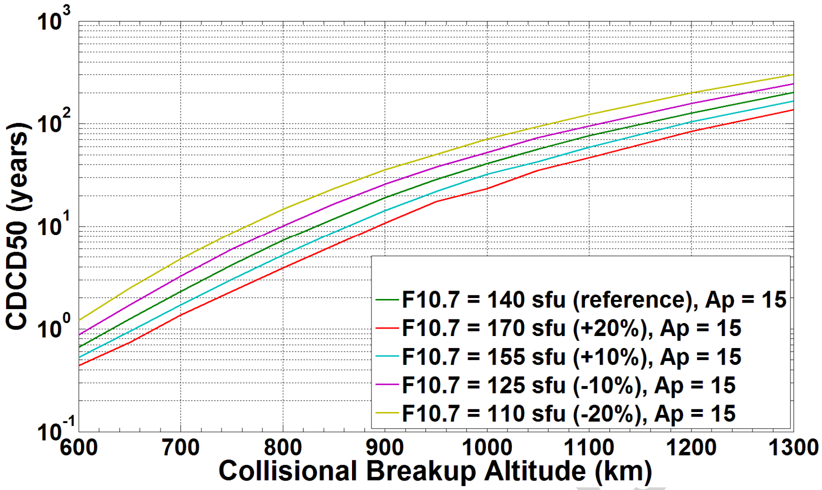

Fig. 2: First halving time of the catalogable fragments generated by a catastrophic collision (CDCD50), as a function of the breakup altitude (in nearly circular orbit) and average solar activity. The results were obtained with the STELA software tool, using the basic cloud properties determined by the authors for the Fengyun 1C, Cosmos 2251 and Iridium 33 catastrophic breakups.

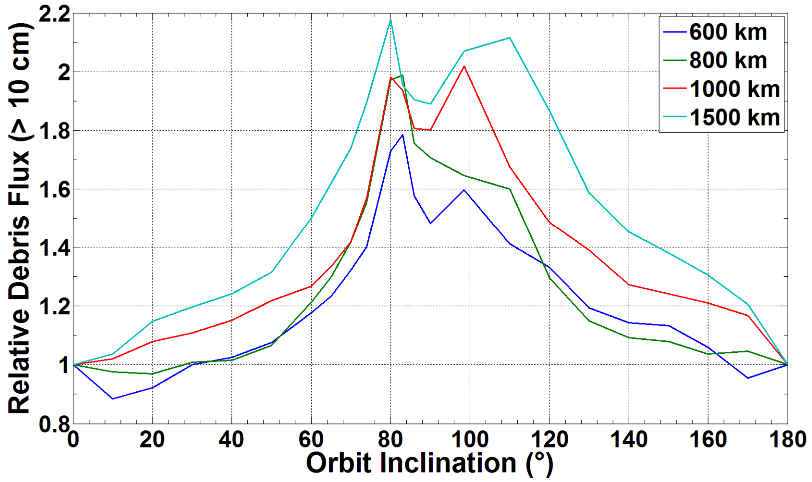

Fig. 3: Plot of z(h,i), for debris ≥ 10 cm, as a function of orbit inclination and altitude (in nearly circular orbit). The orbital debris fluxes were obtained for mid-2014 with the MASTER-2009 model.

Regarding the volume of space affected by the potential breakup and the interaction of the resulting cloud of fragments with the pre-existing debris distribution, we opted for the choice of a function *z*, defined in the following way:

$$z(h,i,d \geq 10cm) \cong \frac{F(h,i,d \geq 10cm)}{F(h,i=0°,d \geq 10cm)} \tag{9}$$

In LEO, it has a strong dependence on the orbit inclination i, but varies relatively slightly with the height h. A representative plot of z, based on debris fluxes computed with the MASTER-2009 model [25], is shown in Figure 3 for some LEO altitudes of interest. The function g in Eq. (1) was therefore defined as follows:

$$g \equiv CDCD50(h,d \geq 10cm) \cdot z(h,i,d \geq 10cm) \tag{10}$$

completing the set up of the ranking R.

IV.II Normalized and Dimensionless Ranking Index

From a practical point of view, it was highly desirable deriving from R an index R_N both normalized and dimensionless. To do so, we reverted again to the average intact object in LEO [13][14][19], defining a reference object with the following characteristics: M_0 = 934 kg, h_0 = 800 km, i_0 = 98.5°. The normalized and dimensionless ranking index R_N then became:

$$R_N \equiv \frac{F}{F_0} \cdot \frac{l(h)}{l(h_0)} \cdot \left(\frac{M}{M_0}\right)^{1.75} \frac{CDCD50(h)}{CDCD50(h_0)} \cdot \frac{z(h,i)}{z(h_0,i_0)} \tag{11}$$

where $F_0 = F(h_0, i_0, M_0)$ and $l(h)/l(h_0) \equiv 1$ when $h > h_0$. The latter cut off, set at a lifetime around 200 years (see Figure 1), was introduced to avoid giving too much relative weight to objects with very long lifetimes, much longer than any reasonable temporal horizon for the current modeling and technology projections.

The ranking index meaning is easy to understand, because R_N is referred to an average intact object in LEO placed in the most popular orbital regime, the sun-synchronous one. The number obtained for a specific object "proportionally" compares its latent detrimental effects on the long-term debris environment with those of the reference body. In other words, if $R_N = 3$ were obtained, for example, this would imply, according to the ranking scheme devised, that the object under evaluation would be equivalent, concerning its long-term detrimental effects on the debris environment, to 3 reference objects in sun-synchronous orbit, and in case of candidate search for active debris removal it should be ranked accordingly.

IV.III Logarithmic Ranking Index

Notwithstanding the straightforward meaning of R_N, its values may span a range of many orders of magnitude, so a logarithmic index R_{NL} might be more functional in certain cases. It was defined in the following way:

$$R_{NL} \equiv \log_{10}(R_N) + 1 \tag{12}$$

in order to obtain $R_{NL} = R_N = 1$ for the reference body, and $R_{NL} \geq 0$ when $R_N \geq 0.1$, i.e. 1/10 of the ranking index for the reference body.

IV.IV Ranking of the Unmaneuverable Italian Objects

The ranking scheme developed and presented in the previous sections was applied to the abandoned or unmaneuverable Italian objects deployed in LEO as of mid-2014. For each of them, the normalized lifetime $l(h)$, $CDCD50(h)$ and $z(h,i)$ were estimated with the available models and software tools, while the flux of debris able to induce the catastrophic fragmentation of the target, taking into account the appropriate relative velocity distribution and a critical breakup threshold [26] of 40,000 J/kg, was computed with the just released NASA ORDEM 3.0 model [27] for mid-2014. The results obtained are summarized in Table 5.

Object	Ranking index R_N	Logarithmic ranking index R_{NL}
IRIS stage	2.391×10^{-5}	-3.621
Temisat	7.404×10^{-2}	-0.131
Itamsat	5.585×10^{-3}	-1.253
Megsat 1	3.944×10^{-5}	-3.404
Unisat	6.418×10^{-6}	-4.193
Unisat 2	2.194×10^{-5}	-3.659
Unisat 3	1.399×10^{-3}	-1.854
AGILE	3.786×10^{-6}	-4.422
Edusat	7.396×10^{-5}	-3.131
LARES	5.038	1.702
ALMASat 1	4.392×10^{-7}	-5.357
E-ST@R	5.000×10^{-9}	-7.301
Unicubesat-GG	6.874×10^{-9}	-7.163
Unisat 5	4.490×10^{-5}	-3.348
Unisat 6	1.721×10^{-4}	-2.764

Table 5: Ranking indices of the Italian abandoned or unmaneuverable objects in LEO regarding either their latent detrimental effects on the debris environment, over the next 200 years, or the priority of active removal. They are related to a reference object of 934 kg in an 800 km sun-synchronous orbit, for which $R_N = R_{NL} = 1$.

It is worth noting that 14 objects out of 15, i.e. more than 93%, exhibited a very small ranking index, making them relatively undangerous for the debris environment over the coming two centuries, corresponding all together to just 8% of an average abandoned intact object in a 800 km sun-synchronous orbit. Concerning the noticeable exception, LARES, as already pointed out it will remain operational for a very long time, but is completely passive and the extremely long lifetime orbit selected for scientific reasons is unfortunately characterized by a local peak of debris density. However, the probability of incurring in a collision leading to a catastrophic breakup will be of the order of 10^{-4} in the next 200 years.

IV.V Ranking of the Highest Mass Objects in LEO

As of mid-2014, there were 23 abandoned objects in LEO in the 8-9 metric tons mass class [1]. They were the following, ordered as a function of growing altitude:

(1) 2 Zenit 2nd stages ($h \approx 640$ km, $i = 98°$);
(2) The Envisat satellite ($h = 765 \times 767$ km, $i = 98°$);
(3) 1 Zenit 2nd stage ($h = 801 \times 814$ km, $i = 98°$);
(4) 18 Zenit 2nd stages ($h \approx 845$ km, $i = 71°$);
(5) 1 Zenit 2nd stage ($h = 986 \times 1006$ km, $i = 99°$).

The ranking evaluation exercise was repeated for these high mass objects too, giving the results summarized in Table 6.

Object	Ranking index R_N	Logarithmic ranking index R_{NL}
Zenit R/B (1)	0.278	0.444
Envisat (2)	7.126	1.853
Zenit R/B (3)	23.00	2.362
Zenit R/B (4)	21.99	2.342
Zenit R/B (5)	168.7	3.227

Table 6: Ranking indices of the 23 most massive objects abandoned in LEO, as of mid-2014, regarding either their latent detrimental effects on the debris environment, over the next 200 years, or the priority of active removal. They are related to a reference object of 934 kg in an 800 km sun-synchronous orbit, for which $R_N = R_{NL} = 1$.

Therefore, according to the ranking scheme proposed, the 23 most massive objects abandoned in LEO as of mid-2014, i.e. the Envisat spacecraft and 22 Zenit rocket bodies (R/B), regarding either their latent detrimental effects on the debris environment, over the next 200 years, or the priority of active removal, were on the whole equivalent to 595 average intact objects in a 800 km sun-synchronous orbit. This figure compares well with a previous estimate obtained by the authors with a more simplified ranking scheme [13].

V. CONCLUSIONS

As of mid-2014, 1 spent upper stage and 14 abandoned or unmaneuverable spacecraft belonging to Italy were present in LEO, representing approximately 0.5% of the intact objects entirely resident there. Their combined mass was close to 1219 kg and the total average tumbling cross-section was almost 9 m^2. The whole collision expectancy with orbital debris $\geq$ 10 cm was 1.94×10^{-5} per year, while the catastrophic collision expectancy was 9.68×10^{-5} per year (Table 7).

Among these objects, 40% were compliant with the IADC "25 year rule" for post-mission lifetime, but such a percentage was 75% for the satellites launched after the ASI signature of the *European Code of Conduct for Space Debris Mitigation*, at the beginning of 2005. If the objects already decayed are taken into account, the overall compliance with the end-of-life disposal recommendation, over 50 years of Italian space activity, was 64%, with a current trend leaning in between 80% and 90%. The approval of international mitigation guidelines for end-of-life disposal, also with the active Italian participation, had therefore a significant impact on the way space projects were conceived and implemented, including the management of the reentry phase.

Object	Yearly collision expectancy with debris ≥ 10 cm	Yearly collision expectancy with critical impactors
IRIS stage	2.38×10^{-6}	2.86×10^{-6}
Temisat	1.18×10^{-6}	5.37×10^{-6}
Itamsat	7.95×10^{-7}	9.32×10^{-6}
Megsat 1	1.12×10^{-6}	2.78×10^{-6}
Unisat	4.02×10^{-7}	2.22×10^{-6}
Unisat 2	4.37×10^{-7}	3.09×10^{-6}
Unisat 3	1.04×10^{-6}	1.23×10^{-5}
AGILE	2.03×10^{-6}	1.98×10^{-6}
Edusat	6.10×10^{-7}	6.31×10^{-6}
LARES	3.36×10^{-7}	3.51×10^{-7}
ALMASat 1	5.50×10^{-7}	5.30×10^{-6}
E-ST@R	4.56×10^{-8}	3.23×10^{-6}
Unicubesat-GG	6.48×10^{-8}	4.90×10^{-6}
Unisat 5	4.22×10^{-6}	1.52×10^{-5}
Unisat 6	4.24×10^{-6}	2.16×10^{-5}

Table 7: Yearly expectancy of collisions with orbital debris ≥ 10 cm, or able to induce the catastrophic breakup of the target, assuming a critical breakup threshold of 40,000 J/kg. The results were obtained with ORDEM 3.0 in mid-2014.

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Short biography of Luciano Anselmo

Researcher of the Italian National Research Council (CNR) since 1985, he was involved in space mission design, analysis and support in the field of astrodynamics, and also carried out risk satellite reentry predictions for the Italian authorities. During the last 25 years he was deeply committed to orbital debris modeling, managing or participating in several contracts on the subject and representing Italy in various international committees and forums, including the Inter-Agency Space Debris Coordination Committee (IADC). He is a full member of the International Academy of Astronautics (IAA).

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Since 1986 Carmen Pardini has served as a research scientist in the Space Flight Dynamics Laboratory of ISTI (formerly CNUCE), an Institute of the Italian National Research Council (CNR) in Pisa. Her areas of research include astrodynamics, mission analysis and design, satellite reentry predictions, software development, space debris modeling and mitigation. In 1998, she was appointed as Technical Point of Contact of the Italian Space Agency (ASI) for the coordinated reentry prediction campaigns of the Inter-Agency Space Debris Coordination Committee (IADC). Since 2000, she is ASI representative in the IADC Working Group 2 "Environment and Database". She is a member of the Space Debris Technical Committee of the International Academy of Astronautics (IAA).

Highlights

- The compliance of the Italian satellites in LEO with the disposal guidelines for space debris mitigation was evaluated.
- An improvement following the adoption of international guidelines and standards was shown.
- A new ranking index was developed to estimate the long-term criticality of space objects for the orbital debris environment.
- This new scheme could also be used for active debris removal priority listing.