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THE 1997.0 CNUCE ORBITAL DEBRIS REFERENCE MODEL

C. Pardini[•], L. Anselmo[•], A. Rossi[•], A. Cordelli[*] and P. Farinella[+]

A new orbital debris environment model (CODRM-97) has been developed. It includes the objects with mass ≥ 1 mg produced by 140 energetic breakups, 16 liquid metal coolant leaks from nuclear powered spacecraft, international launch activity and space operations.

Each fragmentation or leakage was simulated with the most appropriate models and parameters, and the resulting debris clouds were propagated, including all the significant orbital perturbations, to the chosen reference epoch (January 1, 1997). At this point, the particles still in orbit were merged with the catalogued objects present in space at the same time. In total, more than 65 millions of particles with mass ≥ 1 mg were generated during the simulations and more than 52 millions resulted still in orbit at the reference epoch.

Preliminary comparisons with the measurements available below 1000 km seem to indicate that the CODRM-97 predictions come short by a factor 2-3 for centimeter sized debris and by an order of magnitude for particles with diameters close to 1 mm. This deficiency might reflect, in part, an intrinsic inadequacy of the breakup models adopted, but probably suggests the presence in space of additional debris sources, not yet included in CODRM-97.

INTRODUCTION

Today earth mission planning and operations must deal with a problem mostly ignored just twenty years ago: non-catalogued space debris. Beside 8000-9000 objects larger than 10-20 cm tracked by the US Space Command sensors, the circumterrestrial space is populated by a very large number of artificial debris, down to sub-millimeter particles, produced over the years and continually replenished by international space activities.

[•] Research Staff of CNUCE/CNR, Via S. Maria 36, 56126 Pisa, Italy (e-mail: c.pardini@cnuce.cnr.it).

[*] Consorzio Pisa Ricerche, Piazza d'Ancona 1, 56127 Pisa, Italy (e-mail: cordelli@apollo.cnuce.cnr.it).

[+] Dipartimento di Matematica, University of Pisa, Via Buonarroti 2, 56127 Pisa, Italy (e-mail: paolof@dm.unipi.it)

Particles in the millimeter and centimeter size range are particularly interesting because they can severely damage critical spacecraft sub-systems. A cost effective shielding against millimeter sized debris is sometime feasible, but the penetration avoidance following the impact of a particle close to one centimeter is much more expensive and difficult to obtain, as the International Space Station designers know well.

Most of the experimental data available in this debris size range comes from dedicated campaigns of radar measurements carried out since 1990 by several facilities in the United States and Europe. The Haystack radar, in particular, provided lot of good measurements, between 0.1 and 10 cm, up to the altitude of 1400 km[1]. The main outcome of such data was to show the very large number of millimeter and centimeter particles present in space, much more than expected.

The modeling community reacted following two complementary approaches. In one of them, environmental debris models were developed emphasizing the consistency with measurements in low earth orbit more than the detailed description of the source mechanisms and mechanics. Such *engineering models*, like NASA's ORDEM96[2], are useful operational tools to predict debris fluxes on low earth satellites, in agreement with the available database and the models used to fit the measurements. The other approach consisted instead in identifying the candidate source and sink mechanisms, modeling in detail each single event able to produce debris and propagating the full population of orbital particles to a given reference epoch. Such *evolutionary models* may, or - more probably - may not, be in agreement with the measurements, providing important clues about the debris possible sources, the consistency of the fragmentation models adopted and so on. The result is the development of new insights.

Our Pisa team has followed this second path since the fall of 1994. In September 1997, we completed our last and much improved debris environment model, the 1997.0 CNUCE Orbital Debris Reference Model (CODRM-97), which superseded our previous CODRM-94[3]. In order to understand the origin and distribution of the artificial debris in the 0.1-10 cm size range, we carried out a massive effort to estimate the contribution of the historical events in orbit able to produce a large number of particles. The sources considered as of January 1, 1997 - reference epoch of our model - were 140 spacecraft and upper stages breakups and 16 NaK liquid metal leaks from the primary nuclear reactor coolant system of the last Soviet radar ocean reconnaissance satellites (RORSATs).

Over the years, a dedicated software system, CLDSIM[4], has been developed, implemented and continually upgraded and improved to simulate the generation and orbital propagation of debris clouds produced by explosions, collisions and RORSAT-like coolant leakage using several model and parameter options. In particular, it includes one breakup model for low intensity explosions, four models for high intensity explosions, two models for collisions and one model for RORSAT-like events. The largest objects (as defined by the user) and a sample of the smallest ones are propagated using an accurate fast orbit propagator (including all the relevant perturbations), or a much faster debris cloud propagator (including only air drag, varying according to the 11-yr solar activity cycle).

Using CLDSIM, each debris generating event was simulated independently with the most appropriate models and parameters, and the resulting debris clouds were propagated - including all the relevant perturbations - to the chosen reference epoch: January 1, 1997, 00:00 UTC. At this point, the particles obtained were merged with the US Space Command catalogued objects, propagated to the same epoch. A reasonable orbit was found also for hundreds of catalogued objects related to classified US military missions and for which two-line orbital elements were not available. The resulting model, CODRM-97, included all the simulated particles heavier than 1 mg still in earth orbit. With the area/mass relationship adopted, 1 mg corresponds to an average diameter of about 0.89 mm.

In total, more than 65 millions of particles heavier than 1 mg were generated during the simulations and more than 52 millions resulted still in orbit at the reference epoch. The number of objects actually propagated was close to 200,000, with sampling factors ranging typically from 1/1000 for the smallest particles (< 10 mg) to 1/5 in the 1-100 g range. The objects heavier than 100 g were propagated one by one. The total mass in orbit obtained at the reference epoch was 3431 metric tons, while the overall cross-sectional area was 37,569 m^2. The 99.94% of the mass and the 99.79% of the cross-sectional area resulted concentrated in the catalogued population.

FRAGMENTATION MODELS

CLDSIM simulates a breakup/leakage event by a random extraction of fragments mass/diameter from a given distribution[4]. To generate CODRM-97 we used only a subset of the fragmentation models built in CLDSIM. The models selected are presented in the following sections.

Low Intensity Explosions

To represent the fragment mass distribution for low intensity explosions we adopted the classical relationship[5]:

$$N(m) = \begin{cases} 0.171 M_t e^{-0.6502\sqrt{m}} & m \geq 1.936 \\ 0.869 M_t e^{-1.8202\sqrt{m}} & m < 1.936 \end{cases} \tag{1}$$

where M_t is the exploding mass and N is the cumulative number of fragments with mass larger than m. M_t and m are in kg.

High Intensity Explosions

For high intensity explosions, two mass distribution models were used. Both assume that the 90% of the exploding mass M_t follows an exponential distribution law, while the 10% follow a power law. The requirements of mass conservation and function continuity set the value of the numerical coefficients. One of the models is similar to that adopted in the NASA's EVOLVE program[6]:

$$N(m) = \begin{cases} 9.4561 \cdot 10^{-3} M_t / m & m < 0.015 \\ 0.7901 M_t e^{-1.8202\sqrt{m}} & 0.015 \le m < 1.936 \\ 0.1555 M_t e^{-0.6502\sqrt{m}} & m \ge 1.936 \end{cases} \tag{2}$$

where M_t and m are in kg. The other one was proposed in 1995 by R. Jehn and T. Parrinello of ESA/ESOC[7] (the masses are expressed in kg):

$$N(m) = \begin{cases} N_0 e^{-c\sqrt{m}} & m \ge 0.05 \\ 0.439\left(\dfrac{m}{0.1 \cdot M_t}\right)^{-0.75} & m < 0.05 \end{cases} \tag{3}$$

N_0 and c are calculated such that mass conservation is granted and the function $N(m)$ is continuous.

Collisions

The fragment mass distribution adopted in the NASA's EVOLVE program has been used for collision modeling[6]:

$$N(m) = 0.4396\left(\frac{M_e}{m}\right)^{0.7496} \tag{4}$$

The total mass of the ejecta M_e is given by $1.15v^2m_p$ – where v is the relative impact velocity in km/s and m_p is the projectile mass – if the ratio $(1.15v^2m_p)/M_t < 0.1$ (craterization regime, with $M_t \equiv$ target mass). Otherwise, a catastrophic breakup occurs and $M_e = M_t + m_p$.

RORSAT Liquid Metal Leakage

In the last few years the Haystack radar observations led to the detection of a previously unrecognized space debris family, with circular orbits between 600 and 1000 km of altitude (maximum concentration between 850 and 1000 km) and inclinations around 65°.

There were 50000-70000 such particles larger than 8 mm and very few were larger than 3 cm. The radar signatures of these objects were characteristic of conductive spheres at every measured wavelength and their ballistic coefficients were consistent with mass densities around 1 g/cm^3. Due to their orbital and physical properties, these particles were tentatively identified by NASA's Johnson Space Center as droplets of liquid sodium-potassium (NaK) coolant leaked from one or more of the nuclear powered radar ocean reconnaissance satellites (RORSATs) launched by the former Soviet Union.

Following an extensive analysis in the United States and Russia, this hypothesis is now strongly supported by most of the experts that analyzed the experimental and theoretical evidence available. The origin of this unusual source of space debris can be traced back to the *Cosmos 954* malfunction that led, on January 1978, to the light radioactive contamination of a sparsely inhabited area of northern Canada. To prevent the occurrence of a similar mishap in the future, the Soviets redesigned the RORSATs, developing a way to eject the fuel core from the reactor at the end of the mission. This would ensure the complete burning of the naked fuel core during an accidental reentry in the earth atmosphere, as effectively demonstrated five years later by *Cosmos 1402*.

However, the design change affected also the nominal missions (16 up to the program termination on 1988). At the conclusion of each successful flight at very low altitude, the nuclear reactor section was boosted up to an 800-900 km graveyard orbit - as before the *Cosmos 954* accident - but with the important difference that the fuel core was there ejected in any case (in the case of *Cosmos 1900*, the graveyard orbit reached was lower – around 700 km – for a problem on board). The fuel core separation was accompanied by a loss of sealing in the primary reactor coolant loop, containing 13 kg of liquid NaK. Therefore, a leakage of NaK droplets might have, and probably did, occurred. The secondary reactor coolant loop, with 26 kg of liquid NaK, was designed to maintain, instead, its sealing.

For these reasons, we decided to incorporate in CODRM-97 also such a source. By fitting, with the least square method, the size distribution curve observed by the Haystack radar[1] – for droplets in the 0.5-4.7 cm range – and assuming that the 16 leakage events were comparable, we obtained the following size distribution, applicable to each single case:

$$N(d) = 4.881 \cdot 10^{-3}\, d^{\,-2.6277} \qquad 5.0 \cdot 10^{-3} \le d \le 4.7 \cdot 10^{-2} \tag{5}$$

where $N(d)$ is the cumulative number of droplets with a diameter larger than d (meters). The particle mass was computed assuming a spherical shape and a sodium-potassium density of 0.9 g/cm^3.

Particles smaller than 5 mm where not included in CODRM-97 for the following reasons:

- Due to sensor limitations, they were not detected, so there are no data available;

- A large fraction of such small particles could have been evaporated or decayed in the years elapsed since the leaks occurred;
- The small drops eventually left in orbit should be only a small fraction, less than 10%, of the total population of millimeter sized particles, continually generated by other sources.

On the other hand, it seems that drops of 5 cm or more were not produced in significant numbers.

A sodium-potassium leakage according to Eq. (5) was simulated for each of the 16 RORSATs left in orbit between *Cosmos 1176* (launched on 1980) and *Cosmos 1932* (launched on 1988). The events were assumed to occur immediately after the nuclear core ejection in graveyard orbit and every cloud of NaK droplets was propagated to the CODRM-97 reference epoch.

Area-to-Mass Ratio

To relate the mass m (kg) and the cross-sectional area A (m^2) of space objects, we adopted the classical relationship[8]:

$$m = \begin{cases} 62.013A^{1.13} & A \geq 8.04 \cdot 10^{-5} \\ 2030.33A^{1.5} & A < 8.04 \cdot 10^{-5} \end{cases} \tag{6}$$

Object diameters were obtained assuming a spherical shape. For explosions and collisions, the mass of each fragment was used to compute a corresponding average cross-section by inverting Eq. (6); then, the actual area was randomly extracted from an appropriate log-normal distribution[7].

For the catalogued objects, when the mass was known with a reasonable level of confidence, the corresponding area was obtained using Eq. (6). On the other hand, if reasonable values for the mass were not available, the measured radar cross section was equated to the area and the corresponding mass was finally computed, again with Eq. (6).

Fragment Velocity Distribution

To find the orbits of the breakup fragments, a velocity distribution for the ejected material was needed. For explosions, we adopted the relation[8]:

$$\log(\overline{\Delta V}) = -0.0676(\log d)^2 - 0.804\log d - 1.514 \tag{7}$$

where $\overline{\Delta V}$ is the average ejection velocity (km/s) and d is the fragment diameter (meters). To model the expulsion of the RORSAT's coolant droplets, we used the same formula, but the resulting velocity increment was divided by a factor 10.

For collisional events, we adopted instead the following equation[9]:

$$\log\left(\frac{\overline{\Delta V}}{V_i}\right) = \begin{cases} A + B\left[\log\left(d / d_m\right)\right]^2 & d \geq d_m \equiv E^{1/3} / C \\ A & d < d_m \equiv E^{1/3} / C \end{cases} \tag{8}$$

where Vi is the relative impact velocity (km/s) and E is the impact kinetic energy (J). If the particle diameters are expressed in meters, the constants used assume the following numerical values:

$$A = -0.125$$
$$B = -0.0676$$
$$C = 8.01 \cdot 10^8$$

Known the average $\overline{\Delta V}$, the actual velocity increment of each fragment (ΔV) was obtained from the triangular distribution[10]:

$$\Delta V = \begin{cases} \overline{\Delta V}\left(0.1 + 0.6\sqrt{3y}\right) & 0.00 \leq y < 0.75 \\ \overline{\Delta V}\left(1.3 - 0.6\sqrt{1 - y}\right) & 0.75 \leq y \leq 1.00 \end{cases} \tag{9}$$

where y is a random number between 0 and 1. Because all the breakup events were assumed isotropic, the velocity vector of each simulated fragment was obtained by adding to the velocity of the parent body a vector of magnitude ΔV and random direction. From the state vector of the parent body at the breakup epoch, the computation of the orbit of each fragment produced was then easy.

DEBRIS PROPAGATION

The propagation to the environment reference epoch (January 1, 1997) of catalogued objects and breakup debris clouds was performed using three trajectory propagators: DCP, FOP and ASAP.

The Debris Cloud Propagator (DCP) is a very fast semi-analytic orbit predictor that includes only the orbital perturbations due to atmospheric drag[11]. The atmospheric density is provided by a modified Jacchia-Roberts 1971 model, that takes into account the long-term variations due to the solar activity 11-yr cycles. The Fast Orbit Propagator (FOP) uses the variation of parameters theory and takes into account the main orbital perturbations, i.e. geo-potential harmonics up to the fifth order and degree, air drag (modified Jacchia-Roberts 1971 density model), moon and sun third body perturbations and solar radiation pressure with eclipses[12]. The Artificial Satellite Analysis Program (ASAP) is a numerical code using the Cowell method and including the same perturbations considered in FOP, but not necessarily the same models[13].

All the catalogued objects were propagated using FOP. On the other hand, all the droplets associated with the RORSAT leakage events were propagated, due to their large number (~87,000) and orbital characteristics, with DCP. For the debris produced by explosions and collisions, the procedure was more complex. The fragments heavier than 100 g were in fact propagated one by one, but the smaller objects generated were too many to be treated at the same manner. Therefore, the debris produced by each breakup were suitably sampled and only the sorted out particles were propagated, with the implicit assumption that the orbital evolution of the debris represented by them would be the same. In the 90% of the breakup events, the following sampling factors were used, as a function of the debris mass m (kg):

- 1/1000 for $10^{-6} \leq m < 10^{-5}$
- 1/100 for $10^{-5} \leq m < 10^{-4}$
- 1/10 for $10^{-4} \leq m < 10^{-3}$
- 1/5 for $10^{-3} \leq m < 10^{-1}$

In the remaining cases, the sampling factors used were:

- 1/10000 for $10^{-6} \leq m < 10^{-5}$
- 1/1000 for $10^{-5} \leq m < 10^{-4}$
- 1/100 for $10^{-4} \leq m < 10^{-3}$
- 1/10 for $10^{-3} \leq m < 10^{-2}$
- 1/5 for $10^{-2} \leq m < 10^{-1}$

Any fragment with $m \geq 100$ g and the sampled debris were propagated with FOP, except those coming from three explosions in geosynchronous orbit, for which ASAP was used.

In total, about 200,000 objects were propagated to the CODRM-97 reference epoch, for time intervals ranging from a few months to more than 35 years. More than 2000 hours of CPU time on a DEC 2100 workstation were needed to complete the computations involved.

ORBITAL BREAKUPS

Following the first on-orbit fragmentation, the explosion of the *Transit 4A* rocket body on June 29,1961, 140 breakups have been recorded until January 1, 1997 (reference epoch of our environment model)[14]. These account for over forty percent of the catalogued population and the majority of the debris in the 1-10 cm size range. Generally, a fragmentation may result from either explosions or collisions, but explosions have been, so far, the primary contributors to the orbital debris environment. A variety of on-orbit explosive mechanisms is possible, including propulsion-related explosions, deliberate breakups, and catastrophic failure of internal components, such as batteries. On the other hand, before January 1, 1997, only three collisional breakups have been reasonably confirmed:

- The American anti-satellite test in which a solar observation satellite, named *Solwind* (*P78-1*), was destroyed by the impact with an air-launched miniature homing vehicle;
- The military satellite *USA 19*, which deliberately collided with its *Delta* upper stage during the *Delta 180* Strategic Defense Initiative orbital mission. But, probably, an explosive charge was detonated on-board one of the vehicles just before the collision occurred[15];
- The first accidental hypervelocity collision between two catalogued objects, on July 24, 1996, when the stabilization boom of the French satellite *Cerise* was cut by a fragment produced in the breakup, on November 1986, of the *Ariane* third stage used to launch the *Spot 1* satellite. Despite this, the satellite is still functioning, the *Ariane* fragment seems intact, and only one new piece of debris was generated.

Table 1 lists the number of the past fragmentation events in terms of the most probable breakup cause[16].

Table 1

ON-ORBIT BREAKUPS PROBABLE CAUSE

Breakup Probable Cause	Number of Breakups
Deliberate (explosions + collisions)	50
Propulsion Related	40
Unknown	40
Battery	9
Accidental Collisions	1
TOTAL	**140**

Breakup Classification

During the development of the ESA Meteoroid and Space Debris Terrestrial Environment Reference Model (MASTER), an explosion intensity parameter B was introduced to fit the fragment mass distribution observed in ground tests and orbital breakups[17]. The parameter B has been estimated for most of the historical explosions considered in our model[18], so we used it to broadly classify the explosion intensity in three classes. For the events not yet included in the original MASTER list[18], we estimated the intensity parameter by analogy with similar breakups.

Low intensity explosions ($B < 1.3$) were simulated using the fragment mass distribution given in Eq. (1), high intensity explosions ($1.3 \leq B < 2.3$) with Eq. (3), and very high intensity explosions (B ≥ 2.3) with Eq. (2). The classification and the corresponding modeling of the following events were based on additional information and analysis, taking into account radar observations (if available), orbital and size distribution of the resulting catalogued objects and possible breakup causes:

- *Cosmos 1275*: very high intensity explosion, Eq. (2);
- *Ekran 2*: low intensity explosion in geosynchronous orbit, Eq (1);
- *Cosmos 1484*: high intensity explosion of a pressurized tank of about 30 kg, Eq. (3);
- "*Mystery Family*": high intensity explosion that reproduced the size distribution observed by Haystack, Eq. (3).

The "*Mystery Family*" is a debris cloud observed by the Haystack radar, with inclinations close to 90° and altitudes between 600 and 1000 km[1]. The debris size distribution is similar to that originated from *Cosmos 1484*, but no candidate source has been identified so far. However, we took into account such debris as well, by introducing a generic explosion event which reproduced the distribution of fragments observed by Haystack.

Table 2

BREAKUP EVENTS CLASSIFICATION AND MODELING

CLASSIFICATION	NUMBER OF BREAKUPS
Low intensity explosions [Eq. (1)]	60
High intensity explosions [Eq. (3)]	63
Very high intensity explosions [Eq. (2)]	15
Collisions [Eq. (4)]	1
Collisions [no simulation]	1
TOTAL	**140**

Table 3

CROSS-CORRELATION BETWEEN BREAKUP CAUSE AND MODELING

CAUSE	BREAKUP MASS DISTRIBUTION MODELING			
	Eq. (1)	**Eq. (3)**	**Eq. (2)**	**Eq. (4)**
Propulsion related	15	18	7	0
Deliberate explosion	28	21	0	0
Battery	3	5	1	0
Unknown	14	19	7	0
Intentional collision	0	0	0	1
TOTAL	**60**	**63**	**15**	**1**

The *Solwind* breakup was the only one simulated using the collisional mass distribution given in Eq. (4); the *Delta 180* event was considered a low intensity explosion and, consequently, modeled using Eq. (1), while the collision involving *Cerise*, due to the nature of the event, did not need any modeling at all, having produced only one new detectable fragment.

The classification of the 140 historical breakup events considered in CODRM-97 is summarized in Tables 2 and 3.

CATALOGUED OBJECTS

On January 1, 1997, at 00:00 UTC, there were 8478 catalogued objects in orbit around the earth. About 900 more objects were occasionally tracked by the US Space Command, but not yet included in the official catalog. Payloads account for 28% of the catalogued population, but operational satellites represent only the 5-6%. Derelict rocket bodies are the 18%, operational debris the 11% and the fragments released by catastrophic breakups and anomalous events account for the remaining 43%.

For the major 4367 unclassified objects, a complete orbital state vector (two-line elements) was obtained from a Jet Propulsion Laboratory public database (ftp @ kilroy.jpl.nasa.gov). Major means the objects having an international designator with letter suffix A through K. For other 3733 smaller unclassified objects, the semi-major axis, eccentricity and inclination at epoch were obtained from the NASA's *Satellite Situation Report*, while the angular orbital parameters (right ascension of the ascending node, argument of perigee and mean anomaly) were randomly generated. For 378 objects, mostly related to classified US military missions, no orbital information was available from official sources. However, a deep and critical review of the open literature available on the subject (both in print and electronic form), together with our independent analysis, made possible to obtain reasonable values for the orbital elements of these objects too.

The spatial density of the catalogued objects, propagated with FOP to the reference epoch, is shown in Figures 1 and 2 as a function of the altitude.

CODRM-97

The simulated debris clouds, produced by the 140 fragmentation[14] and 16 RORSAT leakage events considered in our modeling effort, were propagated to the chosen reference epoch, including particles with mass $m \geq 1$ mg. Because we supposed all the objects heavier than 300 g to be generally tracked by the current US Space Command sensor network, and therefore included in the catalogued population, they were removed from the simulated debris clouds. Even the objects with 50 g $\leq m \leq$ 300 g, corresponding to diameters of 5-11 cm, are often detected by the space surveillance sensors, mostly in very low orbit, but the catalogue is far from complete in such size interval. Therefore, all the objects with $m \leq$ 300 g were retained in our simulated environment.

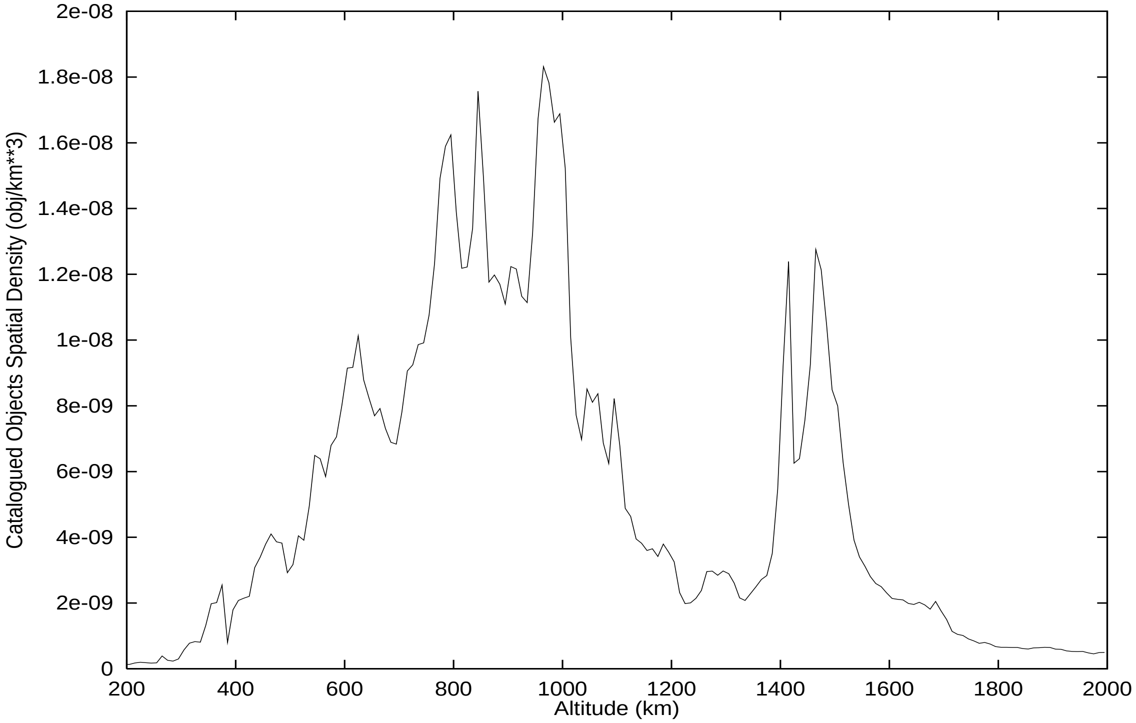

Figure 1. Catalogued Objects Spatial Density Below 2000 km

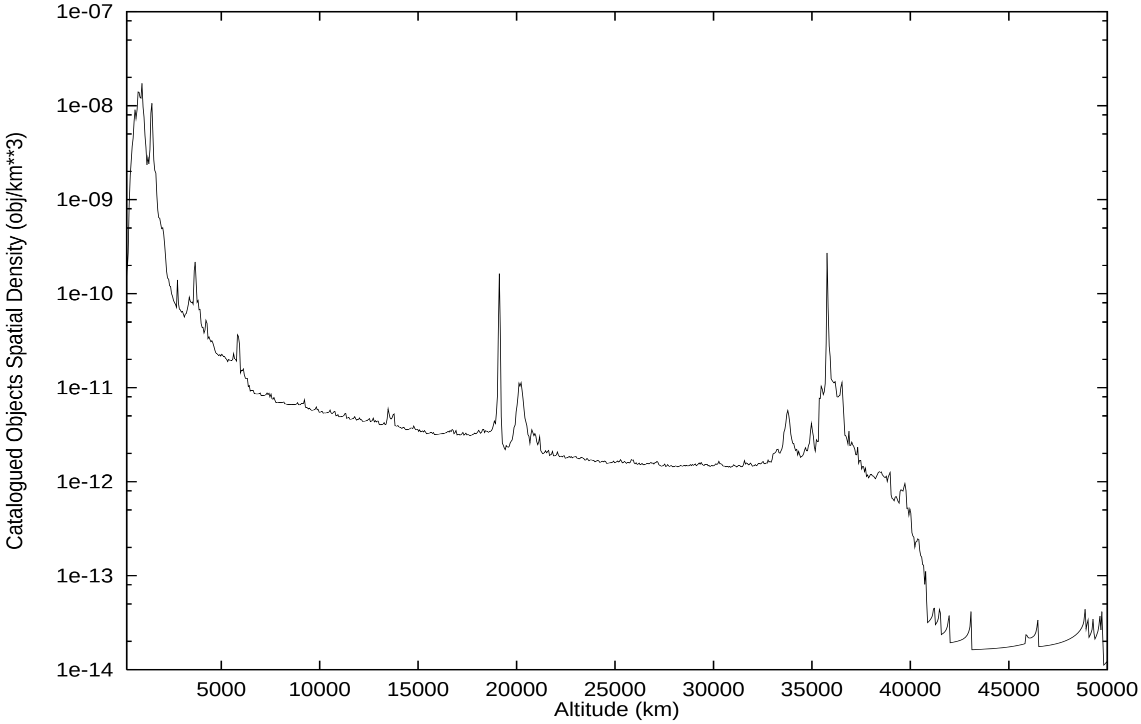

Figure 2. Catalogued Objects Spatial Density Below 50000 km

CODRM-97 was obtained by merging the artificial debris environment so computed with the catalogued population. The lower mass limit is 1 mg, and the maximum altitude considered is 100,000 km. Table 4 summarizes the distribution of the CODRM-97 objects ($m \geq 1$ mg) as a function of the altitude. Further details are presented in Tables 5-7.

Table 4

CODRM-97 OBJECT DISTRIBUTION ($m \geq 1$ mg) BELOW A GIVEN ALTITUDE

Altitude (km) [≤]	Average Number of Objects	Number of Crossing Objects	Average Total Mass (kg)	Average Total Area (m^2)
500	124 272	1 901 341	824 842	8 204
1000	1 861 126	16 238 195	1 977 820	21 229
2000	5 696 171	24 802 235	2 431 360	26 536
5000	12 564 892	28 790 455	2 570 352	28 120
50000	46 442 536	52 246 464	3 425 329	37 498
100000	52 246 484	52 246 484	3 430 694	37 569

Table 5

CUMULATIVE NUMBER OF OBJECTS LARGER THAN A GIVEN DIAMETER

Diameter [≥]	Cumulative Number of Objects
0.89 mm	52 246 484
1 mm	41 085 484
5 mm	508 594
7 mm	270 003
1 cm	144 654
2 cm	49 691
5 cm	19 580
10 cm	11 048

Table 6

CUMULATIVE NUMBER OF OBJECTS LARGER THAN A GIVEN DIAMETER BELOW THE ALTITUDE OF 2000 KM

Diameter [≥]	Average Number of Particles	Number of Crossing Particles
1 mm	4 634 196	19 023 235
5 mm	219 824	312 845
7 mm	124 070	169 404
8 mm	100 214	134 564
1 cm	71 989	94 345
2 cm	27 907	34 983
10 cm	7 189	8 630
20 cm	5 190	6 076

Table 7

CODRM-97 ORBITAL DEBRIS SIZE AND ALTITUDE DISTRIBUTION

Diameter [≥]	h ≤ 500 km	h ≤ 1000 km	h ≤ 2000 km	h ≤ 5000 km	h ≤ 50000 km
1 mm					
Average No.	103 156	1 535 237	4 634 196	10 199 441	36 522 573
Crossing No.	1 448 341	12 585 195	19 023 235	22 029 455	41 085 464
1 cm					
Average No.	1 783	35 203	71 989	90 375	138 127
Crossing No.	10 343	72 224	94 345	98 855	144 634
10 cm					
Average No.	291	4 196	7 189	7 564	10 990
Crossing No.	1 140	6 269	8 630	9 379	11 028

The spatial density distribution as a function of the altitude is shown in Figures 3 and 4 for artificial debris larger than 1 mm, 1 cm, and 10 cm.

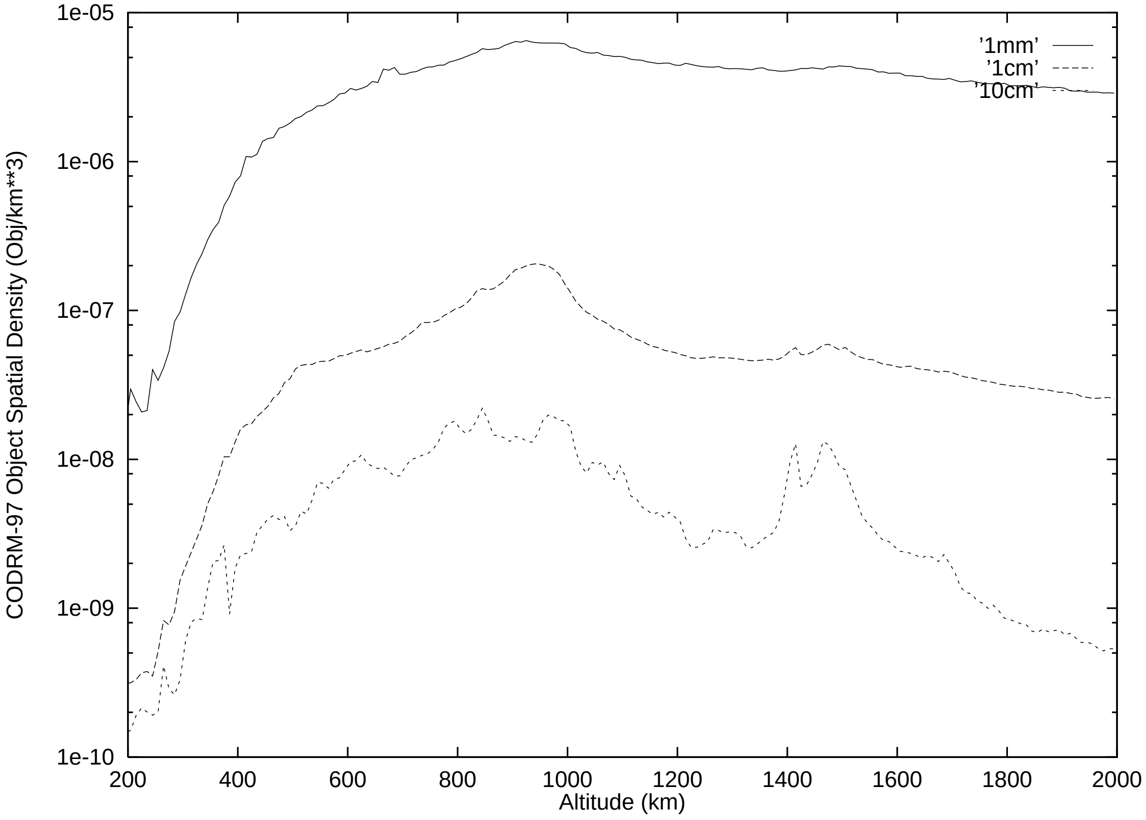

Figure 3. CODRM-97 Spatial Density Below 2000 km for Objects with Diameters ≥ 1 mm, 1 cm, 10 cm

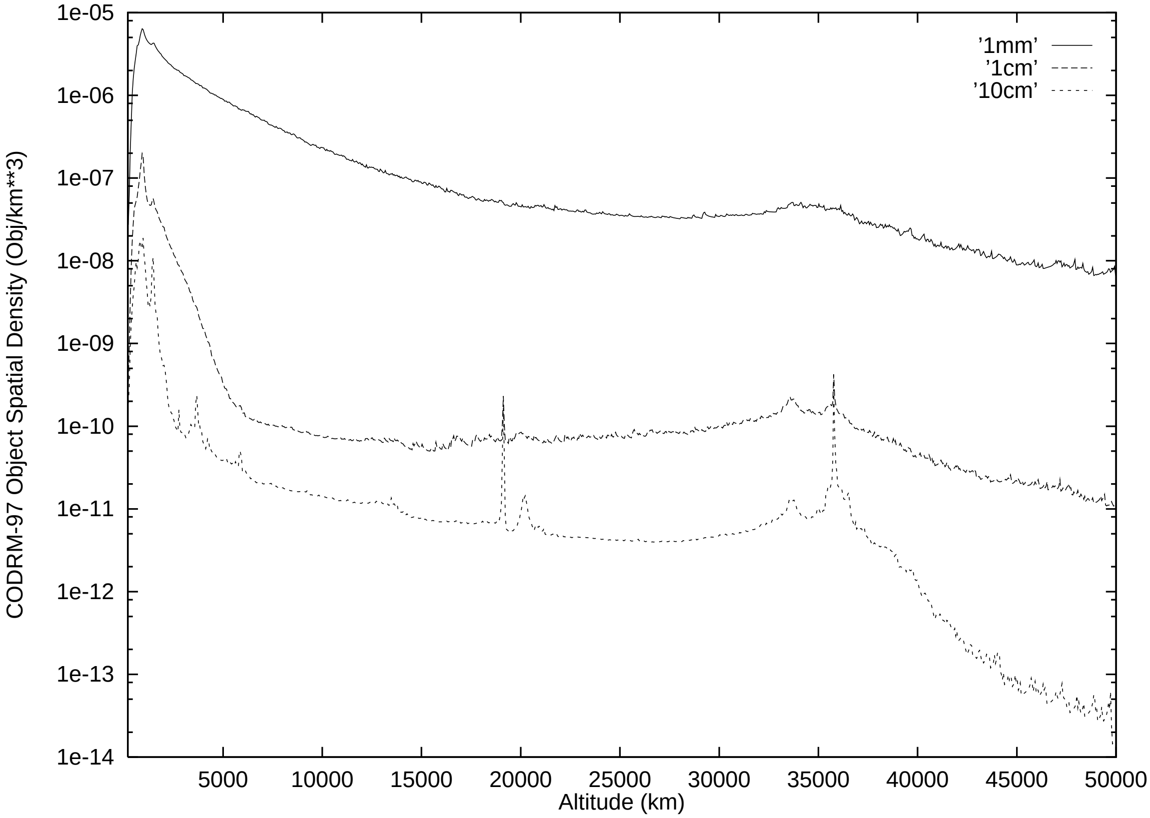

Figure 4. CODRM-97 Spatial Density Below 50000 km for Objects with Diameters ≥ 1 mm, 1 cm, 10 cm

Because each object included in the model is characterized by its mass, area and orbital state vector, CODRM-97 can be used for several purposes, as to investigate in detail the distribution of debris particles in earth orbit up to 100,000 km of altitude, to compute the collision probabilities for specific spacecraft and rocket bodies, to study the effects of debris clouds in high eccentricity orbits or simply as initial background environment for computer programs devised to study the short/long term evolution of orbital debris, such as the Semi-Deterministic Model (SDM) and the Stochastic Analog Tool (STAT) developed in Pisa by our team[7]. Nevertheless, CODRM-97 may also be used for in depth comparisons with radar and optical observations, when and where available, in order to assess the relative importance of the debris sources considered.

At present, the Haystack radar observations[1] and the NASA's ORDEM96 semi-empirical model[2], which combines direct measurements with theoretical analysis, are the most reliable sources of information about the orbital debris environment, at least below 1000 km of altitude. Even though a direct comparison between CODRM-97 and ORDEM96 is not easy, due to the quite different output structure of the two models, as they are implemented so far, a preliminary cross-check below 2000 km indicates that our simulations have generated a lesser number of small particles. For centimeter sized debris, the CODRM-97 predictions come short by a factor 2-3, while for millimeter sized particles the deficit reaches one order of magnitude.

Of course, if the discrepancy observed is real, it might simply reflect an intrinsic inadequacy of the breakup models adopted. This may be in part the case, because we have observed that the mass distributions used for explosions tend to produce too many large fragments (by a factor 5-6), to the detriment of centimeter and millimeter sized particles. But our conclusion, based on experimental fragmentation data and small particle replenishing rate in low earth orbit, is that additional source mechanisms, apart energetic breakups and RORSAT coolant leaks, were and are probably active in space, producing most of the observed millimeter sized debris and a significant fraction of those around 1 cm, at least in specific altitude ranges. The slag material ejected by solid rocket motor burns[19, 20] and the satellites surface degradation produced by the near earth environment (atomic oxygen, thermal cycling, solar radiation and particles, particulate impacts)[21] could in principle account for the observed differences and should be investigated and modeled in detail to test their suitability as the missing debris sources.

This search has not only an academic interest. In fact, the actual artificial debris sources must be clearly identified and their relative impact on the environment assessed in order to derive and implement effective mitigation measures.

CONCLUSION

A new evolutionary orbital debris environment model (CODRM-97) has been developed. It includes the objects heavier than 1 mg produced by 140 energetic breakup events, 16 RORSAT sodium-potassium leaks, launch activity, and space operations. The altitude limit is 100,000 km and the reference epoch is January 1, 1997, but the model was devised to be easily updated with the addition of new launches and orbital breakups.

Preliminary comparisons with the measurements available below 1000 km seem to indicate a deficiency of small debris, due probably to sources not yet included in our model and to the inadequacy of the fragmentation distributions adopted. These topics need further investigations, on both the measurement and modeling side, and we are committed to continue the research in the field. In the meantime, CODRM-97 fares well with respect to the other existing environment models and has the potential to become a useful space engineering tool. It has already been used in our medium/long term analysis of the orbital debris evolution, but might find applications in mission design, analyses and planning.

For this reason we plan the development of the Space Debris Impact Risk Assessment Tool (SDIRAT), a software system built around CODRM-97 to extract debris density, flux, impact probability, relative velocity distribution and other relevant information in a user friendly way. When available, SDIRAT, relying on both graphical and tabular output, could also be used to plan radar and optical debris measurement campaigns.

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