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A SURVEY OF THE PAST ON ORBIT FRAGMENTATION EVENTS THROUGH THEIR CONTRIBUTION TO THE ORBITAL DEBRIS POPULATION

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ABSTRACT

Following the first on-orbit fragmentation, the explosion of the *Transit 4A* rocket body on June 29, 1961, 165 breakups have been recorded until August 31, 2001. So far, only three collisional breakups have been reasonably confirmed, while the remaining 162 fragmentations resulted from explosions.

Aim of this paper is to assess the contribution of these on orbit fragmentation events to the cataloged and undetected orbital debris population. To make this, the larger fragmentation debris were extracted by the U.S. Space Command catalog of August 31, 2001, and subsequently assembled for families or single event, then counted and graphically represented. The contribution to the undetected debris population was investigated using a dedicated software system, named CLDSIM, to simulate and propagate the debris clouds produced by each fragmentation event. The characteristics and properties of the fragmentation debris population, obtained by merging the cataloged and undetected particles, were then analyzed.

INTRODUCTION

After more than forty years of space activities, almost 27,000 objects have been officially cataloged, with approximately one-third of them still in orbit around the earth. The detectable debris environment population (up to more than 8800 objects with a limiting diameter of roughly 10 cm in Low Earth Orbit – LEO – and about 1 m in high earth orbit) is continuously monitored by the space surveillance systems of the United States and Russia.

During the last decade, the examination of returned spacecraft surfaces, together with an effective search work made by the Haystack and Haystack Auxiliary (HAX) radars, the Goldstone and Arecibo radio telescopes, the NASA's Liquid Mirror Telescope (LMT) and the NASA's CCD Debris Telescope, have extended the range of orbital debris measurements to particles as small as one micron. Besides the U.S. radar and optical facilities, the German Tracking and Imaging Radar system (TIRA) of the Research Establishment for Applied Science (FGAN) has been used in recent years to establish an independent European data source. The main outcome of all the collected measurements was to show the very large number of millimetric and centimetric particles present in space, much more than expected: tens of thousands of fragments measuring more than 1 cm and hundreds of thousands still smaller debris.

Because the growing accumulation of space debris, such a pollution is becoming a serious threat to space operations. Especially dangerous are the debris in the 1-10 cm size range. Though too small to be tracked by operational systems, they are large enough to cause catastrophic damage to many satellites. So far, breakups of spacecraft and upper stages account for the majority of the undetected debris in the 1-10 cm size range and are likely to play such a role for the immediate future. In fact, despite the active efforts of the spacefaring nations to reduce the probability of such events (by venting residual propellants and discharging other forms of stored energy, in order to "passivate" their systems), the rate of breakup events has not subsided, varying from four to eight per year in the last decade.

Over the years, a massive effort was carried out at CNUCE to estimate the contribution of the historical events in orbit able to produce a large number of particles. As from 1994, various debris environmental models were developed[1,2,3] using a dedicated software system, CLDSIM[4], to simulate the generation and orbital propagation of debris clouds produced by explosions and collisions. Recently, a similar work was repeated to obtain the outcomes of the past on-orbit spacecraft and upper stages breakups until August 31, 2001. Using CLDSIM, each fragmentation event was independently simulated with the most appropriate models and parameters[3], and the resulting debris clouds were propagated[5] – including all the relevant perturbations – to the chosen reference epoch: 31 August 2001, 00:00 UTC. At this point, the particles so obtained were merged with the fragmentation orbital debris of the U.S. Space Command (USSPACECOM) catalog at the same epoch. In this way, the contribution of the known historical fragmentation events to the cataloged and undetected debris population was investigated in terms of the number and spatial distribution of the particles produced.

HISTORICAL FRAGMENTATION EVENTS

Following the first on-orbit fragmentation, the explosion of the *Ablestar* stage on June 29, 1961, 165 breakups (79 upper stages and 86 spacecraft) have been recorded until August 31, 2001. Generally, a fragmentation may results from either explosions or collisions, but explosions have been, so far, the primary contributors to the orbital debris environment. On the other hand, before August 2001, only three collisional breakups have been reasonably confirmed and only the third one resulted to be an accidental hypervelocity collision between two cataloged objects.

A variety of on-orbit explosive mechanisms is possible, including propulsion related explosions, deliberate breakups and catastrophic failures of internal components such as batteries. The breakups classified as accidental have been probably caused by the energy stored on-board a spacecraft/upper stage left in space after the completion of its mission. This residual energy can be both chemical and mechanical, in the form, for example, of residual propellants, pressurized containers (as sealed batteries, thermal and attitude control systems, propulsion systems) and/or momentum devices.

Propulsion Related Explosions

The accidental explosions of spent upper stages have been the primary source of long-lived debris in LEO. The first breakup of this type was the explosion of the *Ablestar* stage, on June 1961, followed by a number of random disintegrations of other rocket stages. So far, the most serious series of launch vehicle breakups involved nine devastating fragmentations of the *Delta* 2nd stages during the period 1973-1991 and, more recently, the ullage motors (SOZ) of the fourth stage of the Russian *Proton* (*SL-12*) launch vehicle. The cause of both these event families is thought to be the same and was attributed to a hyperbolic ignition of the residual propellants due to the tank bulkhead failure, probably caused by a thermal stress.

Delta 2nd stages The *Delta* 2nd stages did not fragment during space operations, but only after they had successfully completed their delivery mission and had been abandoned. Apart from the *Himawari 1* rocket body, that fragmented the same day of the launch (on 14 July 1977), the other eight stages experienced breakups after:

- more than one month (*NOAA 3* r/b on December 28, 1973);
- almost one year (*NOAA 4* r/b on August 20, 1975, *Landsat 2* r/b on February 9, 1976 and *NOAA 5* r/b on December 24, 1977);
- nearly three years (*Landsat 1* r/b on May 22, 1975, *Landsat 3* r/b on January 27, 1981 and *Nimbus 7* r/b on December 26, 1981);
- almost 16 years (*Nimbus 6* r/b on May 1, 1991).

All the *Delta* stage explosions took place in LEO and produced a large number of long-lived debris, most of which are still in orbit.

Proton Block-DM Ullage Motors (SOZ) The *Astron* mission led to the first detected breakup of a *Proton Block-DM* ullage motor on 3 September 1984. At present, about 200 *Proton SL-12* have been launched and 24 explosions of these small engines have been recorded. Of these, 3 occurred in LEO, 10 in a GLONASS transfer orbit and 11 in a geostationary transfer orbit. Even if preventive measures have already been adopted to avoid a recurrence of this type of problem on future missions, a large number of these engines, yet not exploded, remains in orbit: the last recorded explosion occurred on July 14, 2001 and involved a SOZ launched before the implementation of such measures.

Pegasus HAPS The most severe in orbit breakup yet recorded was represented by the explosion of the *STEP M2* rocket stage (a *Pegasus* Hydrazine Auxiliary Propulsion System: HAPS) on June 3, 1996. It represented the first known explosive breakup of a carbon-composite tank in earth orbit.

The known historical breakups of rocket bodies, probably as a by-product of their propulsion systems, are listed in Table 1.

Breakups of Spacecraft

Intentional Breakups At least 52 of the 89 spacecraft breakups have been probably the result of intentional actions. Of these, the following events could have been induced by a self-destruction mechanism on-board the satellite:

- 9 breakups during the Soviet Anti SATellite (ASAT) Tests. These tests began in 1968 and were characterized by the planned disintegration of the ASAT interceptor (the weapon loaded with explosive material), as it approached the previously-launched target. Most of these experiments were carried out in the early seventies and were stopped at the beginning of the eighties;
- 17 fragmentations of the *Oko*-class Soviet Early Warning Satellites. Launched into Molniya orbits between 1976 and 1983, these satellites were normally observed to disintegrate in orbit. Probably, their breakup was caused by an on-board explosive charge, that should have destroyed the satellite in the case of a malfunction. Only the 18th, and last event of this class of satellites (the *Cosmos* 1701 breakup, on 29 April 2001), was dissimilar to the previous ones. In fact, the *Cosmos* 1701 fragmentation was assessed to be caused by the aerodynamic loading, probably due to the low perigee of the satellite[6];

Table 1. Historical Breakups of Rocket Bodies

ROCKET BODY	NUMBER OF BREAKUPS	CATALOGED OBJECTS (August 2001)
CIS		
BRIZ	1	20
KOSMOS 2nd Stage	2	106
MOLNIYA 3rd Stage	3	7
PROTON Block DM	2	0
SOZ	24	53
TSYKLON 3rd Stage	4	92
VOSTOK 2nd Stage	3	14
ZENIT 2nd Stage	3	211
US		
ABLESTAR Stage	1	188
AGENA D Stage	2	345
CENTAUR Stage	1	8
DELTA 2nd Stage	9	934
PAM-D Upper Stage	2	0
PEGASUS HAPS	1	126
SATURN S-IVB Stage*	3	0
TE 364-4 Stage	1	0
TE-M-364-15 Upper Stage	1	0
TITAN II G	1	0
TITAN TARNSTAGE	3	43
USA 19 R/B	1	0
ESA		
ARIANE (1,2,3,4) 3rd Stage	8	93
Japan		
H-II 2nd Stage	1	1
China		
CZ-4	2	302
ALL ROCKET STAGES	79	2543

* The fragmentation of the *AS-203* r/b was intentional.

- 19 fragmentations of a class of Soviet military photoreconnaissance satellites. Their nominal mission profile foresaw a re-entry of the film material within a capsule specifically designed to survive the rigors of the re-entry. If the retro-burn failed, or there were other malfunctions preventing the landing within the Soviet/Russian territory, the satellite was probably made to explode through an on-board self-destructing system;
- 1 command breakup of the man-related spacecraft *Cosmos* 57. Its fragmentation was probably caused by an on-board

misinterpretation of the operational ground instructions. This would have caused the activation of the self-destructing device;

- 2 satellites (*1966-088A* and *1966-101A*) of the Soviet Fractional Orbit Bombardment System (FOBS) Tests, that exploded soon after the orbital injection.

Other deliberate fragmentations involved the following vehicles:

- the stage *Saturn S-IVB* (*AS-203* r/b), that was intentionally subjected to dynamic integrity tests after its orbital insertion;
- the solar observation satellite *Solwind P78-1* that, during the only confirmed American ASAT test, 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[7].

Electrical Battery Failures In 1978, the Soviet *Ekran 2* satellite experienced an explosion in geosynchronous orbit. The cause of the incident was attributed to an over-pressurized battery. According to Russian information sources, the same kind of problem could have also caused the on orbit breakups of the satellites *Cosmos 1691* and *Cosmos 1823*. The fragmentation event of *Cosmos 1275*, on 24 July 1981, was reclassified from a collision back to unknown[8]. Since there was nothing internal to the satellite, which could have caused the destructive explosion, it is possible that this satellite had been lost due to electrical batteries failures.

At least in four cases the Soviet anti-satellite targets disintegrated some time after the ASAT tests have been carried out. Since the ASAT targets did not carry the explosive charge of the weapons, it is possible that their breakup could have been caused by a failure of the on-board electrical batteries.

Accidental Collisions Until July 1996, no satellite was definitely known to have experienced a breakup due to an accidental collision in space. The first accidental hypervelocity collision between two cataloged objects occurred 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 was recovered, the *Ariane* fragment seems intact, and only one new piece of debris was generated.

Breakups for Unknown Reasons If the cause of a breakup has yet to be determined, it is said that the fragmentation has occurred for unknown reasons: some would be undoubtedly propulsion related, some might have been intentional, while others might actually mask secret operational activities. The cause of many fragmentations remains unknown, in part due to the limited data available for the analysis.

The *OPS 3031* and *PAGEOS* were inflated spheres with masses, respectively, of 4 and 55 kg. The first disintegrated the same day of the launch (on February 16, 1966) in a short-lived orbit. It decayed, with all the debris generated, within one week from the launch. The *PAGEOS* satellite was extensively observed and photographed around the world for almost ten years since the launch, in June 1966. It experienced at least three fragmentations (12 July 1975, 20 January 1976 and June 1978). A variety of possible causes were investigated, including static electric discharge, but no definitive agent was identified.

The satellite *Cosmos 1484* – the last of the Soviet experimental Meteor-Priroda remote sensing satellites – was launched on July 24, 1983, and failed in February 1984, when it was abandoned. At just past noon of the 18 October 1993, the satellite broke up at an altitude of about 552 km. This breakup was discussed by McKnight[9], quoting that, on the base of the observations done, the spacecraft remained virtually intact, with no apparent rupture of the main body or solar panels. Even if one of the suggested hypotheses for breakup was a battery failure, further investigations will be needed to identify the area from which the debris were ejected, together with the breakup cause.

As far, the majority of satellite breakups for unknown reasons involved the Soviet ELINT Ocean Reconnaissance Satellites (EORSAT). These satellites began flying in 1974 and just the first of the series, the *Cosmos 999* satellite, broke up about four months after launch. The EORSAT program foresaw an increase of the orbital period of these satellites at the end-of-operations and, in the majority of cases, the satellite was observed to fragment during the successive period of orbital decay. There are no apparent reasons for these fragmentations, although the events are generally judged as intentional.

Table 2. Historical Breakups of Satellites

TYPE OF MISSION	SATELLITES	NUMBER OF BREAKUPS	CATALOGED OBJECTS (August 2001)
	CIS		
ASAT Tests	Weapons: Cosmos 249, 252, 374, 375, 397, 462, 886, 970, 1174. Targets: Cosmos 248, 839,880, 1375	Weapons: 9 Targets: 4	Weapons: 321 Targets: 127
Communication	Cosmos 1691, Ekran 3, Molniya 3-16, Molniya 3-36, Molniya 3-26	5	10
Early Warning	Cosmos 862, 903, 917, 931, 1030, 1109, 1124, 1172, 1191, 1217, 1247, 1261, 1278, 1285, 1317, 1456, 1481, 1701	18	51
EORSAT	Cosmos 699, 777, 838, 1094, 1167, 1220, 1260, 1286, 1306, 1355, 1405, 1461, 1588, 1646, 1682, 1769, 2313, 2347	18	2
FOBS series	1966-088A, 1966-101A	2	0
Geodesy	Cosmos 1823	1	38
Man-related	Cosmos 57	1	0
Military	Cosmos 95	1	0
Navigation	Cosmos 1275	1	265
Photoreconnaissance	Cosmos 50, 199, 554, 758, 844, 884, 1654, 1813, 1866, 1906, 1916, 2030, 2031, 2101, 2163, 2225, 2243, 2262, 2343	19	0
Remote Sensing	Cosmos 1484	1	4
	US		
Weather	NOAA 8	1	0
Geodesy	OPS 3031	1	0
Geodesy	PAGEOS	1	3
Solar Observation (ASAT test)	Solwind P78-1	1	3
Military	USA 19	1	0
	France		
Military	Cerise	1	1
ALL SATELLITES		86	825

Table 2 lists the known historical satellites breakups caused by explosions, or by a collisional event in the cases of the *Cerise* and *Solwind P78-1* satellites.

Table 3 shows the complete list (with the following abbreviations applied: EN – event number; CATN – USSPACECOM catalog number; MASS – breakup mass; B_E – breakup epoch; SMA, ECC, INC, RAN, AP, AM – parent object semi-major axis, eccentricity, inclination, right ascension of the ascending node, perigee argument and mean anomaly, respectively) of the fragmentation events recorded until August 31, 2001. The masses reported in Table 3 are those adopted at the 14th IADC meeting[10], unless otherwise specified. For later fragmentations events, the values indicated in the NASA's History of On-Orbit Fragmentations[11] were used and, after 1998, the masses were assigned by analogy with similar breakups. Different information sources were utilized in the following cases:

* *Delta* 100 and *Delta* 2000 2nd stage: the masses recommended by P. Anz-Meador (personal communication, 1999) have been used.

** Both PAM-D stages, that are still observed by the U.S. Space Command as intact objects, suffered probably only the loss of nozzle pieces. Some debris was originated by the stage fragmentation, but perhaps only a very small fraction of the body suffered a breakup. For this reason, it was supposed that only a small mass exploded.

*** According to McKnight[9], the spacecraft remained virtually intact after the observed fragmentation event. Thus, only a small fraction of the satellite mass suffered a breakup.

The number of fragmentation events per year is illustrated in Figure 1.

Table 3. Historical Fragmentation Events

EN	SATELLITE NAME	CATN	MASS [kg]	B_E yyyyddd.dd	SMA [km]	ECC	INC [deg]	RAN [deg]	AP [deg]	AM [deg]
1	Transit 4A r/b [Ablestar Stage]	118	625	1961180.25	7316.1	0.0070	66.88	96.15	296.38	206.16
2	Sputnik 29 r/b [Molnyia 8K78 3rd Stage]	443	1500	1962302.50	6608.1	0.0055	65.09	320.83	89.97	157.59
3	Centaur AC-2 r/b [Centaur Stage]	694	4600	1963331.50	7512.3	0.0873	30.40	163.86	106.25	150.12
4	Cosmos 50	919	4750	1964310.50	6589.2	0.0033	51.21	163.40	354.64	318.55
5	Cosmos 57	1093	5500	1965053.41	6672.1	0.0192	64.66	299.73	70.91	132.05
6	Cosmos 61-63 r/b [Kosmos 2nd Stage]	1270	1600	1965074.71	7420.6	0.1065	56.05	357.78	105.60	136.53
7	OV2-1-LCS 2 r/b [Titan Transtage]	1640	1500	1965288.76	7091.3	0.0071	32.20	84.67	194.12	115.81
8	Cosmos 95	1706	400	1966015.50	6743.2	0.0230	48.40	359.87	265.27	172.94
9	OPS 3031	2015	4	1966046.50	6594.4	0.0117	96.59	147.42	127.02	68.79
10	Gemini 9 ATDA r/b [Saturn S-IVB Stage]	2188	3400	1966166.50	6641.6	0.0028	28.74	215.72	138.79	74.64
11	AS-203 r/b [Saturn S-IVB Stage]	2289	26000	1966186.88	6581.6	0.0024	31.99	4.40	22.27	125.47
12	Cosmos U-1	2437	3000	1966260.50	6983.4	0.0638	49.59	342.60	78.99	326.43
13	Cosmos U-2	2536	3000	1966306.50	6893.8	0.0542	49.61	54.91	83.61	68.46
14	Cosmos 199	3099	5500	1968024.50	6658.0	0.0120	65.60	18.28	31.07	17.16
15	Apollo 6 r/b [Saturn S-IVB Stage]	3171	30000	1968104.45	6663.8	0.0115	32.59	290.63	284.30	307.18
16	Cosmos 249	3504	1400	1968294.60	7703.4	0.1098	62.42	118.76	76.78	220.40
17	Cosmos 252	3530	1400	1968306.16	7715.1	0.1051	62.44	77.62	73.67	358.27
18	Cosmos 248	3503	1400	1968306.17	6884.8	0.0042	62.35	77.29	305.17	165.99
19	Meteor 1-1 r/b [Vostok 8A92M Final Stage]	3836	1440	1969087.78	7031.9	0.0277	81.23	32.55	180.68	306.80
20	Intelsat 3 F-5 r/b [TE 364-4 Stage]	4052	1100	1969207.10	9231.8	0.2794	30.45	132.62	183.37	359.50
21	OPS 7613 r/b [Agena D Stage]	4159	600	1969277.66	7380.6	0.0127	69.86	279.98	107.91	11.45
22	Nimbus 4 r/b [Agena D Stage]	4367	600	1970290.13	7450.4	0.0013	99.83	204.07	180.33	127.93
23	Cosmos 374	4594	1400	1970296.63	7701.8	0.1040	62.94	129.10	60.50	285.58
24	Cosmos 375	4598	1400	1970303.25	7689.9	0.1031	62.92	104.70	56.03	8.06
25	Cosmos 397	4964	1400	1971056.60	7765.3	0.1055	65.75	355.11	50.94	9.70
26	Cosmos 462	5646	1400	1971337.70	7392.7	0.1072	65.64	297.12	54.13	4.84
27	Salyut 2 r/b [Proton 8K82K 3rd Stage]	6399	4000	1973093.94	6597.9	0.0039	51.42	332.55	16.50	95.91
28	Cosmos 554	6432	6300	1973126.30	6634.6	0.0142	72.74	303.56	25.41	239.51
29	NOAA 3 r/b [Delta 100 2nd Stage]	6921	800*	1973362.37	7881.9	0.0013	102.14	44.20	112.95	207.95
30	Landsat 1 r/b [Delta 100 2nd Stage]	6127	800*	1975142.76	7146.2	0.0200	98.30	196.22	40.09	287.14
31	Cosmos 699	7587	3000	1975214.68	6804.5	0.0012	64.90	273.26	308.47	232.89
32	NOAA 4 r/b [Delta 2914 2nd Stage]	7532	840*	1975232.54	7828.3	0.0018	101.55	277.87	69.15	165.80
33	Cosmos 758	8191	6200	1975249.79	6624.8	0.0124	67.12	188.66	69.01	326.55
34	Pageos	2253	55	1976020.95	10555.6	0.1187	85.00	209.49	66.58	334.73
35	Cosmos 777	8416	3000	1976025.58	6812.6	0.0001	64.90	302.64	80.64	342.90
36	Landsat 2 r/b [Delta 2914 2nd Stage]	7616	840*	1976170.29	7202.1	0.0121	97.76	95.58	142.68	353.54
37	Cosmos 844	9046	6700	1976207.72	6638.6	0.0146	67.21	151.39	71.68	52.34
38	Cosmos 886	9634	1400	1976362.77	7823.0	0.1084	65.72	336.91	198.79	113.30
39	Cosmos 884	9614	6300	1976364.50	6608.0	0.0106	65.00	228.85	117.59	11.87
40	Cosmos 862	9495	1250	1977074.53	26586.8	0.7305	63.28	97.29	318.67	13.00
41	Cosmos 838	8932	3000	1977137.42	6805.6	0.0012	65.17	129.36	299.44	250.85

42	Himawari 1 r/b [Delta 2914 2nd Stage]	10144	840*	1977195.67	7663.3	0.0977	28.90	270.58	52.56	86.84
43	Cosmos 839	9011	650	1977272.30	7917.0	0.0705	66.01	82.06	351.04	231.73
44	Cosmos 931	10150	1250	1977297.50	26537.4	0.7330	62.74	304.27	318.79	7.34
45	Cosmos 970	10531	1400	1977355.71	7419.3	0.0138	65.69	281.68	114.60	203.92
46	NOAA 5 r/b [Delta 2914 2nd Stage]	9063	840*	1977358.48	7889.1	0.0016	102.12	42.09	54.32	263.71
47	Cosmos 903	9911	1250	1978159.50	26556.8	0.7103	63.32	114.88	319.86	107.57
48	Ekran 2	10365	1750	1978174.50	42183.7	0.0001	8.93	315.03	34.69	211.58
49	Cosmos 1030	11015	1250	1978283.50	26590.9	0.7338	62.78	335.62	318.39	226.22
50	Cosmos 880	9601	650	1978331.71	6962.6	0.0042	65.88	10.38	311.18	314.26
51	Cosmos 917	10059	1250	1979089.65	26596.0	0.6973	63.04	155.63	322.53	352.18
52	Cosmos 1124	11509	1250	1979252.10	26565.5	0.7375	62.78	287.48	318.37	16.50
53	Cosmos 1094	11333	3000	1979260.44	6769.8	0.0009	64.88	271.12	327.85	275.28
54	Cosmos 1109	11417	1250	1980046.50	26569.5	0.7230	63.51	104.38	318.53	172.91
55	CAT r/b [Ariane 1 3rd Stage]	11659	1400	1980106.50	22990.5	0.7151	18.07	93.17	279.47	155.02
56	Cosmos 1174	11765	1400	1980109.30	7395.7	0.0858	65.96	251.07	248.42	160.94
57	Landsat 3 r/b [Delta 2914 2nd Stage]	10704	840*	1981027.18	7282.6	0.0009	99.01	68.58	127.76	145.76
58	Cosmos 1261	12376	1250	1981121.50	26571.3	0.7360	62.87	278.51	316.59	117.43
59	Cosmos 1191	11871	1250	1981134.50	26562.9	0.7170	62.63	197.92	319.70	314.13
60	Cosmos 1167	11729	3000	1981196.38	6779.8	0.0059	65.02	173.78	245.21	126.18
61	Cosmos 1275	12504	800	1981205.99	7362.5	0.0044	83.11	118.98	127.62	302.30
62	Cosmos 1305 r/b [Molnyia 8K78M 3rd Stage]	12827	1100	1981254.50	13577.7	0.4852	62.97	70.77	286.57	286.53
63	Cosmos 1247	12303	1250	1981293.50	26559.1	0.7230	62.95	213.69	318.47	241.71
64	Cosmos 1285	12627	1250	1981325.50	26787.2	0.7350	63.03	248.93	317.15	238.55
65	Nimbus 7 r/b [Delta 2914 2nd Stage]	11081	840*	1981360.50	7320.3	0.0020	99.13	277.15	68.70	16.04
66	Cosmos 1220	12054	3000	1982171.76	7103.7	0.0219	64.92	329.94	0.18	190.31
67	Cosmos 1306	12828	3000	1982193.97	6769.4	0.0011	65.06	40.96	302.47	333.35
68	Cosmos 1260	12364	3000	1982222.98	6976.4	0.0211	65.15	45.11	296.08	184.34
69	Cosmos 1286	12631	3000	1982272.22	6689.7	0.0007	65.14	132.47	263.77	155.20
70	Cosmos 1423 r/b [Molniya 8K78M 3rd Stage]	13696	1100	1982342.61	6707.6	0.0152	62.82	315.84	58.28	220.38
71	Cosmos 1217	12032	1250	1983043.50	26558.1	0.7022	65.20	257.98	274.70	165.47
72	Cosmos 1481	14182	1250	1983190.50	26301.5	0.7340	62.93	165.82	318.12	109.51
73	Cosmos 1355	13150	3000	1983220.97	6754.8	0.0015	64.87	276.37	307.11	17.07
74	Cosmos 1456	14034	1250	1983225.00	26518.7	0.7315	63.44	79.51	319.95	3.75
75	Cosmos 1405	13508	3000	1983354.51	6701.4	0.0016	65.16	124.63	346.08	223.42
76	Cosmos 1317	12933	1250	1984028.50	26563.3	0.7099	62.61	218.66	324.38	37.79
77	Westar 6 r/b [PAM-D Upper Stage]	14694	30**	1984034.90	6689.5	0.0004	28.54	156.37	5.23	354.11
78	Palapa B2 r/b [PAM-D Upper Stage]	14693	30**	1984037.66	6663.6	0.0002	28.59	135.79	323.34	39.95
79	Astron Ullage Motor [Proton SOZ]	13902	55	1984247.84	7102.6	0.0702	51.72	90.54	248.48	312.01
80	Cosmos 1461	14064	3000	1985133.06	7104.9	0.0215	65.00	331.39	232.32	137.76
81	Cosmos 1654	15734	6700	1985172.44	6617.5	0.0094	64.86	359.26	51.70	317.38
82	P-78/Solwind	11278	850	1985256.86	6906.0	0.0033	97.63	182.21	96.14	300.96
83	Cosmos 1375	13259	650	1985294.16	7372.4	0.0013	65.80	349.15	67.51	21.41
84	Cosmos 1691	16139	220	1985326.36	7790.0	0.0007	82.56	341.08	95.56	52.42
85	Cosmos 1714 r/b [Zenit 2nd Stage]	16439	9000	1985362.50	6877.1	0.0484	71.00	282.00	0.00	178.00
86	NOAA 8	13923	1000	1985364.42	7192.3	0.0010	98.70	32.30	190.24	57.79
87	Cosmos 1588	15167	3000	1986054.78	6799.6	0.0013	64.83	246.84	296.20	95.89
88	USA 19	16937	930	1986248.74	6872.3	0.0407	39.16	39.27	12.59	8.39
89	USA 19 r/b	16938	1455	1986248.74	6798.6	0.0291	22.82	19.47	39.05	359.77
90	Spot 1 r/b [Ariane 1 3rd Stage]	16615	1400	1986317.81	7193.3	0.0027	98.76	30.15	43.64	325.69
91	Cosmos 1278	12547	1250	1986335.50	26553.7	0.6599	66.94	287.49	291.95	214.72
92	Cosmos 1682	16054	3000	1986352.84	6807.2	0.0075	64.93	333.86	49.98	285.79

93	Cosmos 1813	17297	6300	1987029.24	6762.2	0.0044	72.62	255.47	167.44	281.38
94	Cosmos 1866	18184	6700	1987207.65	6580.8	0.0083	67.36	98.11	65.26	230.50
95	Aussat K3/ECS 4 r/b [Ariane 3 3rd Stage]	18352	1200	1987262.50	24767.9	0.7333	6.95	175.44	181.96	222.02
96	Cosmos 1769	16895	3000	1987264.50	6755.0	0.0090	65.19	119.66	290.19	325.56
97	Cosmos 1646	15653	3000	1987324.06	6775.7	0.0009	64.83	285.30	237.68	215.82
98	Cosmos 1823	17535	1500	1987351.73	7878.6	0.0025	73.59	183.86	194.54	2.19
99	Cosmos 1656 Ullage Motor [SOZ]	15773	55	1988005.07	7211.5	0.0025	66.50	198.74	264.79	183.53
100	Cosmos 1906	18713	6300	1988031.46	6629.3	0.0023	82.38	253.48	125.54	63.89
101	Cosmos 1916	18823	6700	1988058.19	6565.3	0.0067	64.62	263.87	57.14	18.24
102	Cosmos 1045 r/b [Tsyklon 3rd Stage]	11087	1360	1988130.51	8069.5	0.0020	82.55	353.47	74.28	134.16
103	Cosmos 2030	20124	6700	1989209.17	6556.3	0.0055	67.37	88.57	63.45	354.07
104	Cosmos 2031	20136	6500	1989243.78	6683.2	0.0101	50.35	242.21	58.58	61.14
105	Fengyun 1-2 r/b [CZ-4A Final Stage]	20791	1000	1990277.84	7265.0	0.0013	98.76	288.90	131.78	137.17
106	Cosmos 2101	20828	6500	1990334.72	6614.9	0.0070	64.70	346.52	147.19	331.10
107	USA 68 r/b [TE-M-364-15 Upper Stage]	20978	855	1990335.67	7167.4	0.0081	98.87	3.43	6.38	165.74
108	Cosmos 1519-21 Ullage Motor [SOZ]	14608	55	1991035.13	15952.4	0.5781	52.14	131.15	316.97	201.01
109	Cosmos 2125-32 r/b [Kosmos 2nd Stage]	21108	1435	1991064.57	7970.6	0.0159	74.10	163.40	241.50	72.96
110	Nimbus 6 r/b [Delta 2914 2nd Stage]	7946	840*	1991121.37	7473.4	0.0015	99.46	336.90	103.67	326.65
111	Cosmos 2163	21741	6500	1991340.84	6597.9	0.0060	64.91	36.10	138.81	337.06
112	Cosmos 1710-12 Ullage Motor [SOZ]	16446	55	1991363.37	16143.4	0.5650	65.43	37.16	243.88	337.53
113	OV2-5 r/b [Titan Transtage]	3432	1500	1992052.39	41835.7	0.0085	11.99	22.27	75.71	246.64
114	Cosmos 2054 Ullage Motor [SOZ]	20399	55	1992183.50	20353.4	0.6704	46.95	305.19	319.33	9.57
115	Cosmos 1603 Ullage Motor [SOZ]	15338	55	1992249.61	7217.3	0.0011	66.54	352.31	50.64	181.42
116	Gorizont 17 Ullage Motor [SOZ]	19771	55	1992353.50	15253.0	0.5693	46.48	264.90	354.82	10.57
117	Cosmos 2227 r/b [Zenit 2nd Stage]	22285	9000	1992361.31	7226.7	0.0015	70.85	226.79	83.72	347.99
118	Gorizont 18 Ullage Motor [SOZ]	20116	55	1993012.50	21874.5	0.6976	46.56	212.03	47.85	309.00
119	Cosmos 2225	22280	6500	1993049.78	6610.9	0.0043	65.09	91.81	107.46	7.08
120	Cosmos 2237 r/b [Zenit 2nd Stage]	22566	9000	1993087.30	7223.1	0.0003	70.76	260.31	75.22	8.15
121	Telecom 2B/Inmarsat 2 r/b [Ariane 4 3rd Stage]	21941	1800	1993111.50	24318.4	0.7245	3.44	223.61	111.79	169.56
122	Cosmos 2243	22641	6700	1993117.44	6606.9	0.0055	70.55	56.77	82.07	349.81
123	Cosmos 2259	22716	6700	1993206.50	6626.3	0.0114	67.13	134.47	68.98	113.68
124	Cosmos 1484	14207	30***	1993291.50	6947.4	0.0027	97.35	317.36	328.95	22.85
125	Cosmos 2262	22789	6500	1993352.29	6602.2	0.0075	64.75	208.49	69.53	21.43
126	Clementine r/b [Titan II G]	22974	2860	1994038.72	6610.4	0.0033	67.18	45.80	135.08	113.33
127	OPS 9331-34 r/b [Titan Transtage]	2868	1500	1994039.50	39840.6	0.0053	11.7	307.63	129.58	109.93
128	Astra 1B/MOP 2 r/b [Ariane 4 3rd Stage]	21141	1760	1994117.63	20927.7	0.6824	6.74	139.15	177.67	0.50
129	Cosmos 2133 Ullage Motor [SOZ]	21114	55	1994127.39	17394.5	0.6204	46.83	109.38	161.43	211.96
130	Cosmos 2204-06 Ullage Motor [SOZ]	22067	55	1994312.50	16135.6	0.5749	64.85	65.20	316.80	217.05
131	RS-15 r/b [Briz]	23440	1000	1994360.26	8418.2	0.0190	64.80	83.74	283.80	273.88
132	ETS-VI r/b [H-II 2nd Stage]	23231	3000	1995090.93	18543.1	0.6490	28.50	7.08	16.22	0.00

133	Elektro Ullage Motor [SOZ]	23338	55	1995131.50	24188.1	0.7299	46.71	200.00	300.00	200.00
134	Cosmos 2282 Ullage Motor [SOZ]	23174	55	1995294.50	23990.2	0.7222	46.97	157.14	127.94	322.60
135	Gorizont 22 Ullage Motor [SOZ]	20957	55	1995348.50	12911.7	0.4944	46.50	140.58	117.08	93.62
136	Raduga 33 r/b [Proton Block DM]	23797	3400	1996050.62	24798.6	0.7321	48.58	282.00	0.00	178.00
137	Eutelsat-II-F2 r/b [Ariane 4 3rd Stage]	21057	1760	1996122.50	21974.2	0.6990	6.64	96.14	149.23	37.77
138	STEP M2 r/b [Pegasus HAPS]	23106	97	1996155.63	7081.8	0.0153	81.97	342.00	210.00	35.00
139	Cerise	23606	50	1996205.40	7049.1	0.0017	98.01	141.79	48.51	271.19
140	Cosmos 1883-85 Ullage Motor [SOZ]	18374	55	1996335.50	16121.4	0.5839	64.90	299.57	180.62	312.06
141	Ekran 7 Ullage Motor [SOZ]	18719	55	1997142.50	17985.5	0.6285	46.63	253.04	349.71	162.72
142	Cosmos 2343	24805	6500	1997259.92	6633.0	0.0045	64.85	1.15	113.60	316.27
143	Cosmos 1172	11758	1250	1997357.00	9515.1	0.3214	61.81	113.36	248.22	145.54
144	Asiasat 3 r/b [Proton Block DM3]	25129	3400	1997359.24	24510.5	0.7288	51.45	92.06	1.02	358.60
145	Molniya 3-16	12512	1600	1997036.50	10256.9	0.3698	62.10	87.06	273.44	149.54
146	Electron 1 r/b [Vostok 8A92 2nd Stage]	751	1440	1997042.50	7019.2	0.0811	56.23	135.26	67.55	2.05
147	Meteor 2-16 r/b [Tsyklon 3rd Stage]	18313	1360	1998046.93	7328.5	0.0010	82.55	230.97	335.00	94.03
148	Astra 1A r/b [Ariane 4 3rd Stage]	19689	1760	1998048.52	24724.5	0.7254	7.34	23.80	248.17	181.98
149	Cosmos 2109-2111 Ullage Motor [SOZ]	21013	55	1998073.50	16135.5	0.5725	65.08	306.45	216.72	150.68
150	Cosmos 1987-1989 Ullage Motor [SOZ]	19755	55	1998215.50	16075.5	0.5821	64.92	16.77	182.60	12.04
151	Cosmos 1650-1652 Ullage Motor [SOZ]	15714	55	1998333.50	15852.0	0.5769	52.04	344.46	209.69	94.77
152	Cosmos 2079-81 Ullage Motor [SOZ]	20631	55	1999087.88	16116.5	0.5786	64.81	319.96	199.38	116.27
153	Cosmos 2053 r/b Tsyklon 3rd Stage	20390	1360	1999108.05	6861.4	0.0007	73.52	274.47	15.86	181.58
154	Cosmos 2157-2162 r/b Tsyklon 3rd Stage	21734	1360	1999282.63	7823.5	0.0057	82.57	96.10	135.03	267.00
155	Cosmos 2347	25088	3000	1999326.19	6699.7	0.0120	65.02	331.65	274.17	232.68
156	Gorizont 32 Ullage Motor [SOZ]	23887	55	1999347.00	9257.3	0.2958	46.47	194.32	75.84	315.52
157	CBERS-1 / SACI-1 r/b CZ-4 3rd Stage	25942	1000	2000001.54	7109.5	0.0017	98.54	147.92	14.29	215.93
158	Molniya 3-36	20338	1600	2000140.38	7321.5	0.1163	63.41	346.78	249.23	98.26
159	Gorizont 29 Ullage Motor [SOZ]	22925	55	2000251.00	12044.7	0.4591	46.74	134.75	110.13	78.06
160	Cosmos 2316-18 Ullage Motor [SOZ]	23631	55	2000326.00	15488.7	0.5784	64.44	199.66	213.69	289.67
161	Intelsat VA F15 r/b Ariane 2 3rd Stage	19773	1480	2001001.00	24487.6	0.7186	8.38	73.07	226.48	89.36
162	Molniya 3-26	16112	1600	2001052.89	6786.3	0.0495	62.57	57.67	263.15	164.80
163	Cosmos 1701	16235	1250	2001119.00	19205.6	0.6635	62.90	0.00	90.00	0.00
164	Cosmos 2139-2141 Ullage Motor [SOZ]	21226	55	2001167.29	16010.5	0.5826	64.56	116.99	186.79	155.92
165	Gorizont 27 Ullage Motor [SOZ]	22250	55	2001195.75	9107.1	0.2841	46.47	97.61	152.20	292.82

CONTRIBUTION TO THE CATALOGED POPULATION

On August 31, 2001, the catalog of the U.S. Space Command counted 8989 objects, of which 8843 were in orbit around the earth.

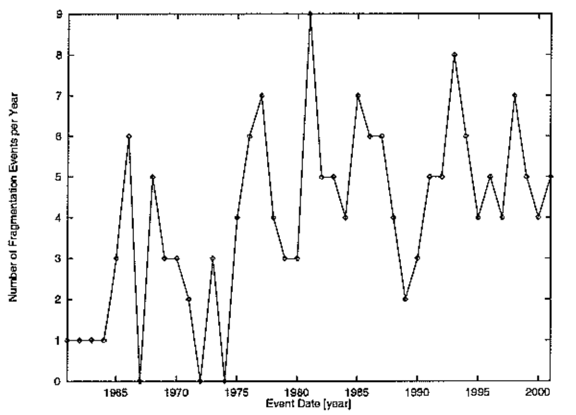

Fig. 1 – Number of fragmentation events per year (June 1961 – August 2001)

Payloads accounted for 2839 objects, but operational satellites were little more than 600. About 1600 of the cataloged objects were derelict rocket bodies discarded after their use, while about 4400 were operational debris and fragments released by catastrophic breakups and anomalous events. The past 165 satellites and rocket stages fragmentations (Table 3) have resulted in 3368 (see Tables 1 and 2) cataloged debris in earth orbit at our chosen reference epoch: 31 August 2001, 00:00 UTC. The remaining 1020 cataloged debris were made by mission-related objects (intentionally released from a spacecraft or rocket body during the course of a mission) and fragments originated by anomalous events.

For most cataloged unclassified objects, a complete orbital state vector (two-line elements) was obtained from a Jet Propulsion Laboratory public database (ftp@kilroy.jlp.nasa.gov). Additional information was extracted from the NASA's *Satellite Situation Report.*

The inclination distribution at the reference epoch of the cataloged debris resulting from the past fragmentation events (Table 3) is displayed in Figure 2. Figure 3 shows their spatial density, as a function of altitude and declination, at the same epoch.

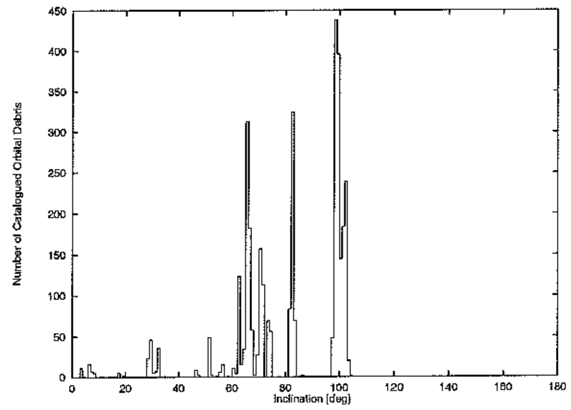

Fig. 2 – Inclination distribution of the cataloged debris from the past on-orbit breakup events

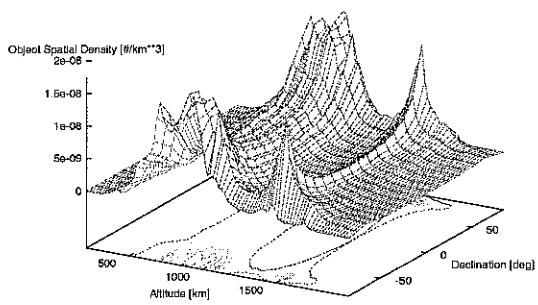

Fig. 3 – Spatial density of the cataloged debris from on-orbit breakup events as a function of altitude and declination

Due to the limited space available, it is not possible to show in this paper the spatial distribution of the cataloged debris for each fragmentation event, or class of events. Therefore, only the following cases are illustrated:

- spatial distribution, in terms of semi-major axis versus eccentricity, of the cataloged debris, at the reference epoch, from the Soviet ASAT weapons breakups (Figure 4);
- Gabbard diagram (Orbital period vs. apogee/perigee altitude), at the reference epoch, of the cataloged fragments from the Pegasus HAPS breakup (Figure 5).

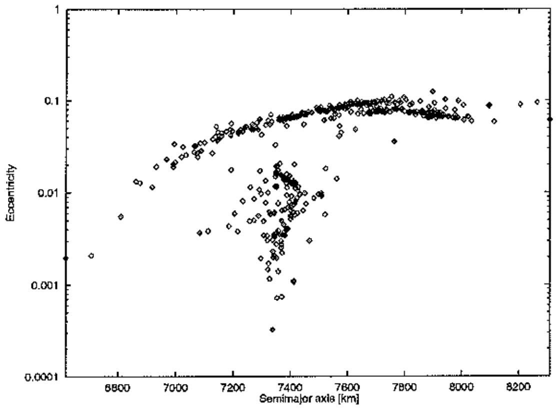

Fig. 4 – Spatial distribution of the cataloged fragments from the Soviet ASAT weapons

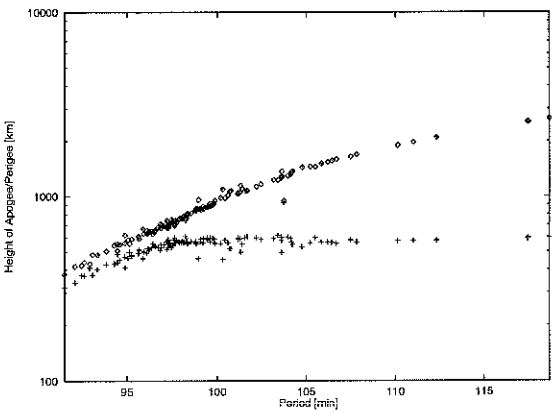

Fig. 5 – Gabbard diagram of the debris cloud from the Pegasus HAPS breakup

UNDETECTED FRAGMENTS SIMULATION

During the last decade, a dedicated software system, named CLDSIM[4], was developed and implemented at CNUCE to simulate the generation and orbital propagation of debris clouds produced by explosions and collisions using several model and parameter options. Using CLDSIM, each of the 165 historical fragmentation events (Table 3) was independently simulated with the most appropriate models and parameters[3], and the resulting debris clouds were propagated with FOP[5] – including all the relevant perturbations – to the chosen reference epoch: 31 August 2001, 00:00 UTC. All these simulations together resulted in 18,773,202 millions of fragments larger than 1 mm, 102,902 larger than 1 cm and 18,367 larger than 10 cm, still in orbit at the reference epoch.

Of course, the correctness of the results obtained strongly depends on the breakup models adopted, and, unfortunately, their validity cannot be easily assessed due to the scarce and incomplete number of observations and measurements available, especially for small particles. Only a rough comparison with the number and spatial distribution of the cataloged debris was possible in a few cases for the larger fragments in low earth orbits. On the other hand, the small fragments, or those resulting from breakups in elliptical or high earth orbits, cannot be easily tracked by the actual observational facilities, making their detection and representation practically impossible.

Therefore, some comparisons have been possible only in a few significant cases, where a considerable number of detected fragments was existing in the catalog.

In this paper, the spatial distribution (in terms of semi-major axis vs. eccentricity on August 31, 2001) of the cataloged objects ("catalogued") and that one of the simulated fragments larger than 10 cm ("simulated_gt_10cm") have been represented for the following fragmentation events:

- the Pegasus HAPS explosion (Figure 6);
- the nine *Delta* breakups (Figure 7);
- the two *CZ-4* fragmentations (Figure 8),

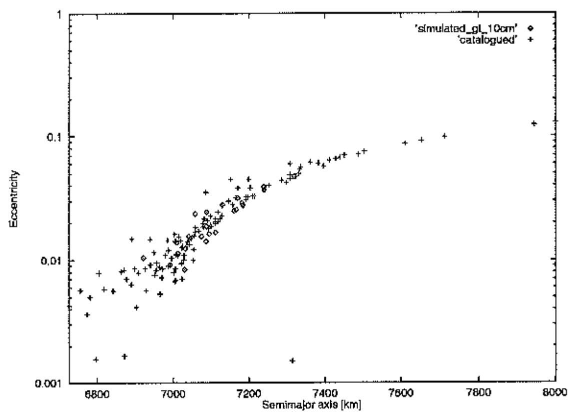

Fig. 6 – Distribution of fragments from the Pegasus HAPS breakup at the reference epoch

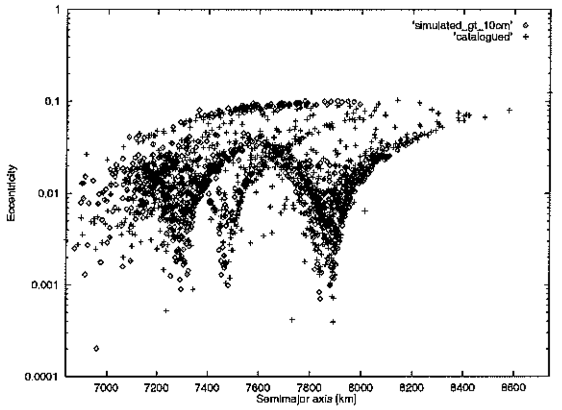

Fig. 7 – Distribution of fragments from the nine Delta 2nd stage explosions at the reference epoch

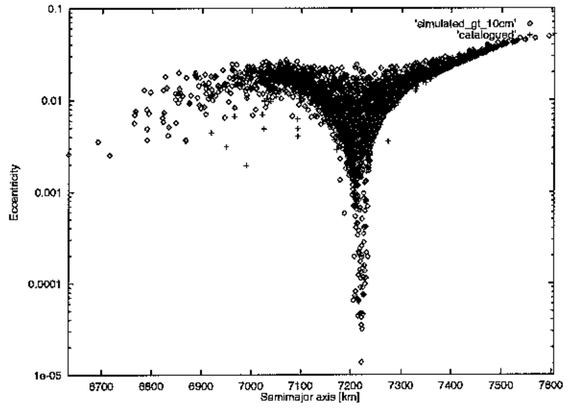

Fig. 9 – Distribution of fragments from the three Zenit 2nd stage explosions at the reference epoch

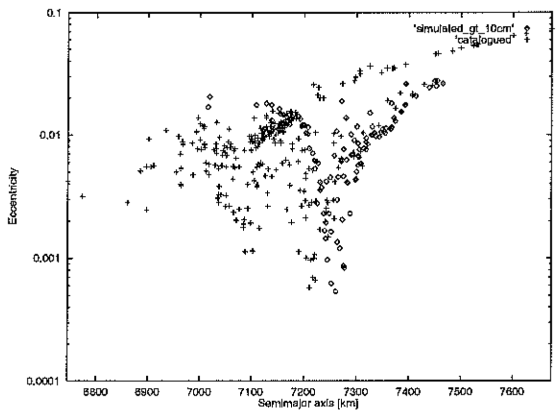

Fig. 8 – Distribution of fragments from the two CZ-4 stage explosions at the reference epoch

Apart from the different number of particles, the simulated spatial distribution of the fragmentation debris larger than 10 cm is quite well representative of the observed one. The number of debris resulting from each fragmentation event depends on the breakup model (low-[12], high-[13], very-high-[14] intensity explosion or collision[14]) used in CLDSIM to simulate the event. In some cases, as in the simulation of the fragments from the three *Zenit* stage explosions (simulated as low-intensity explosions[12]), the number of debris obtained by the simulations was quite higher than the cataloged one (Figure 9). This could reflect an intrinsic inadequacy of the breakup models used, but also a difficulty in tracking and cataloging many particles. Because the first assumption was confirmed by the results of other simulated events, the simulated particles larger than about 15-20 cm were replaced by those of the catalog, preserving some of them to take into account the incompleteness of the catalog itself.

TOTAL CONTRIBUTION TO THE ORBITAL DEBRIS POPULATION

To assess the total contribution of the past on-orbit explosion/collision events to the orbital debris population, an appropriate merging of the simulated objects and the cataloged ones has been carried out. All the cataloged fragments were included, while the objects of the simulated population were retained up to the size of 15 cm. Above this threshold, an appropriate number of simulated debris was randomly sorted out to compensate the incompleteness of the catalog. In between 15 and 20 cm, one out of five objects was retained, while over 20 cm the additional particles selected were one out of fifteen. This choice was consistent with a catalog incompleteness close to 90% in between 10 and 15 cm, 50% in between 15 and 20 cm, and 10% in between 20 and 50 cm.

Therefore, by merging in this way the cataloged fragments with the simulated ones, the population of debris resulting from the past on-orbit explosions and collisions was obtained. The lower size limit was 1 mm, while the maximum orbital altitude considered was 100,000 km.

This population consists of more than 18 millions of fragments larger than 1 mm, 94,730 larger than 1 cm and 9,955 larger than 10 cm, still in orbit at the reference epoch.

The spatial density of fragments larger than 1 mm is displayed in Figure 10, as a function of altitude and declination. Figure 11 shows the spatial density, as a function of the altitude, of debris larger than 1 mm, 1 cm and 10 cm. The distributions in inclination are illustrated in Figures 12 and 13 for debris larger than 1 mm and 1 cm, respectively.

negligible with respect to that of explosions and collisions.

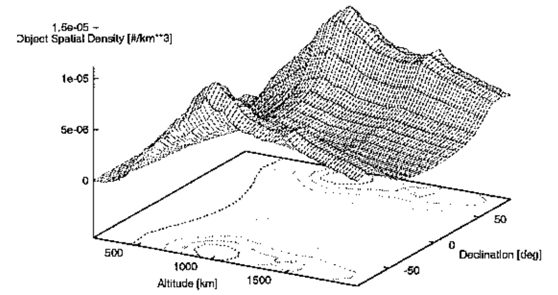

Fig. 10 – Spatial density of fragments with diameter ≥ 1 mm as a function of altitude and declination

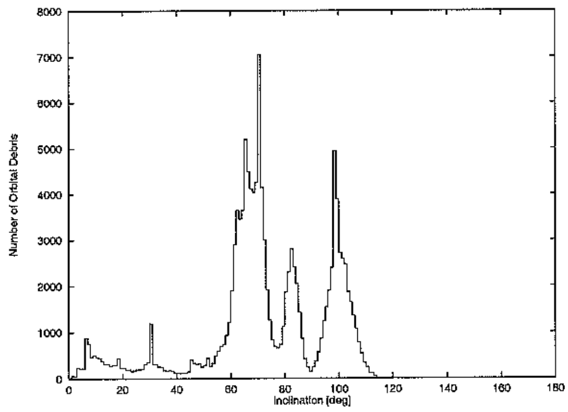

Fig. 12 – Inclination distribution of fragmentation debris with diameter ≥ 1 mm

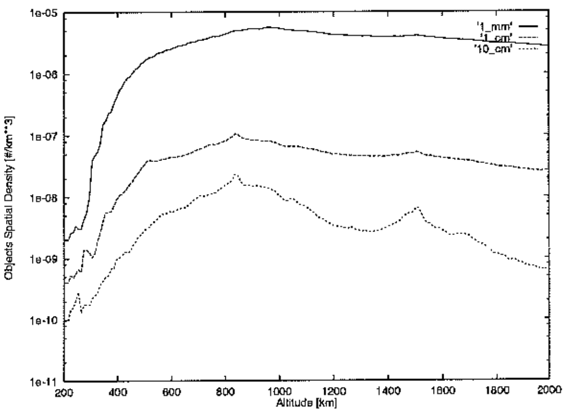

Fig. 11 – Spatial density below 2000 km for fragments with diameter ≥ 1mm, 1cm, 10 cm

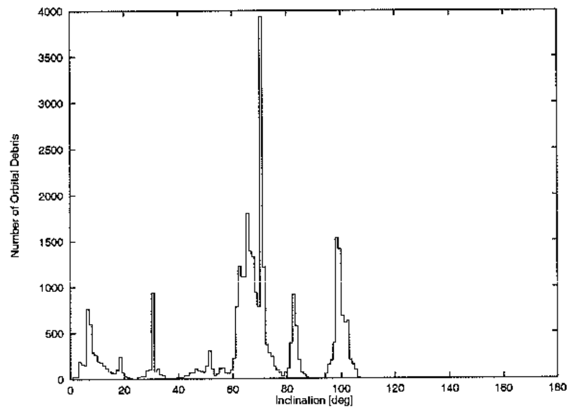

Fig. 13 – Inclination distribution of fragmentation debris with diameter ≥ 1 cm

CONCLUSIONS

At present, satellite and upper stage breakups account for nearly 40% of the tracked objects circling the earth, and the vast majority of the potentially damaging untrackable particles. The on-orbit fragmentations recorded until August 31, 2001, were 165 and they involved 79 upper stages and 86 spacecraft. Only three collisional breakups have been reasonably confirmed, while the remaining 162 fragmentations resulted from explosions. Besides these ones, a few breakups classified as anomalous events have occurred in orbit in the past. However, their contribution to the orbital debris population was

A survey of the past on-orbit fragmentations was carried out in this paper by identifying the spacecraft and upper stages that suffered a fragmentation due to an explosion/collision event. To estimate the contribution of these fragmentations to the cataloged population, all the cataloged orbital debris produced by the past on-orbit explosions and collisions were first extracted by the USSPACECOM catalog of August 31, 2001, and successively assembled for families or single event.

However, the catalog typically includes particles larger than about 10-20 cm in LEO and 1 m in high earth orbit, while a fragmentation event could produce thousands, or even millions, of smaller particles, depending on the type and intensity of the event itself. Many breakup fragments in LEO could have already been reentered due to the atmospheric drag, but a very high number of particles is still in orbit, as the results of the ground observations and the in-situ measurements confirm.

To investigate the characteristics of this undetected population, a massive effort was carried out at CNUCE during the last years. It consisted in the simulation and orbit propagation of all debris clouds produced by the past on orbit breakups. Recently, using the software system CLDSIM, the known 165 breakups listed in Table 3 were simulated and the resulting population was merged with the cataloged fragmentation debris. In this way, it was possible to assess the contribution of the past on-orbit fragmentations to the population of small particles.

The results obtained have pointed out the production of a very large number of fragmentation debris: more than 18 millions larger than 1 mm would still be in orbit at the reference epoch and, among these, a considerable quantity of particles would be able to produce serious damages to satellites. These results also confirmed the extreme necessity of the mitigation measures adopted to prevent future on-orbit explosions, in order to avoid, or at least reduce, the generation of a so large amount of detrimental debris in space.

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