Italian National Research Council

Institute of Information Science and Technologies

REVIEW OF THE UNCERTAINTY SOURCES AFFECTING THE LONG-TERM PREDICTIONS OF SPACE DEBRIS EVOLUTIONARY MODELS

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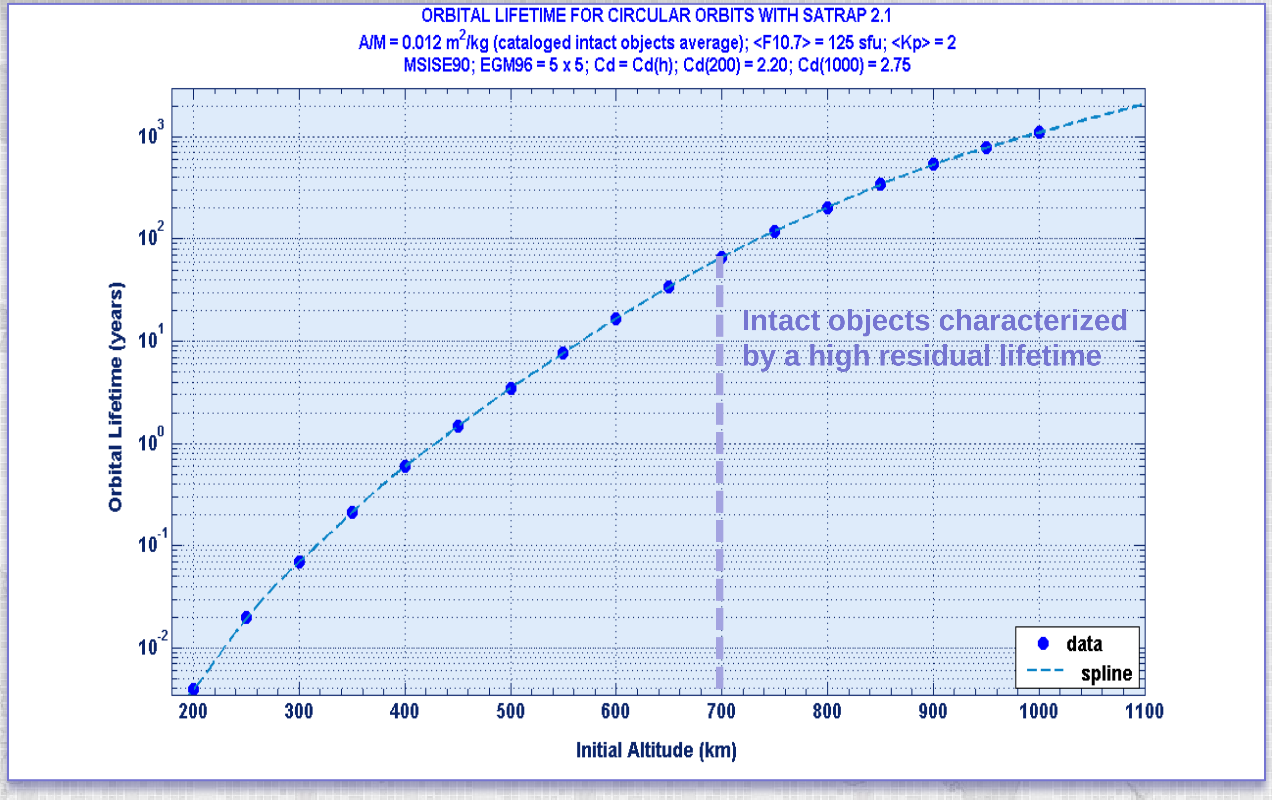
3rd European Workshop on Space Debris Modelling and Remediation
CNES HQ, Paris, France, 16-18 June 2014

Introduction [1]

- From a purely mathematical point of view, **the artificial debris population in low Earth orbit above ~700 km should be intrinsically instable**, due to the physics of mutual collisions and the relative ineffectiveness of air drag and other perturbations in removing intact objects and fragments



ORBITAL LIFETIME FOR CIRCULAR ORBITS WITH SATRAP 2.1
A/M = 0.012 m^2/kg (cataloged intact objects average); <F10.7> = 125 sfu; <Kp> = 2
MSISE90; EGM96 = 5 x 5; Cd = Cd(h); Cd(200) = 2.20; Cd(1000) = 2.75

Intact objects characterized by a high residual lifetime

- However, from the practical point of view of space access and exploitation, **the accurate evaluation of the time scale characterizing the expected pace of debris growth is of fundamental importance to factor in the operational impact**, the technological advances, the economic consequences, and the possible need of remediation measures

Introduction [2]

Point at issue

with the current, planned and predictable practices, HOW MUCH TIME WOULD BE NEEDED FOR THE SITUATION TO BECOME UNSUSTAINABLE, from an economical and operational point of view

→ *YEARS?*

→ *DECADES?*

→ *CENTURIES?*

→ *MILLENNIA?*

- To address this important question, **since the 1980's several sophisticated long-term debris evolutionary models have been developed** at NASA and around the world (since 1992 also in Italy, at CNR, with ESA and ASI funding)

- **During the last three decades these evolutionary models have considerably grown in complexity and capability**, incorporating accurate orbit propagators, detailed launch traffic models, all the relevant sources and sinks mechanisms, updated on-orbit explosion/fragmentation statistics, improved breakup models for explosions and collisions (in terms of debris number, area, mass and velocity distributions), various methods for collision probability estimation, Monte Carlo statistical methods based on discrete-time Markov chains, etc.

Introduction [3]

- ❑ Currently these models are frequently used to probe reasonable future scenarios, in order to evaluate the relative effectiveness of mitigation and remediation measures, and their predictions are compared and fine tuned, for instance in the framework of IADC promoted studies

- ❑ Unfortunately **these predictions, in particular beyond a few decades in the future, are still affected by considerable uncertainty**, much more than that resulting from the analysis of Monte Carlo statistics, as the latter only measures the intrinsic variability in the occurrence of stochastic events, like on-orbit explosions and collisions, but not the potential impact of other important unpredictability sources

- ❑ Moreover, **several important uncertainty sources are completely outside the control of modelers**, i.e. cannot be reduced with better models and more powerful computers

Uncertainty Sources [1]

- ❑ *Under the full control of modelers*
  - ➢ **Trajectory propagators**
  - ➢ **Collision probability estimation**
- ❑ *Under the partial control of modelers*
  - ➢ **Initial debris environment**
  - ➢ **Atmospheric density models**
  - ➢ **Collision energetic threshold for catastrophic breakup**
  - ➢ **Collision geometry leading to catastrophic breakup**
  - ➢ **Collision class (debris vs. debris, debris vs. intact, intact vs. intact) leading to catastrophic breakup**
  - ➢ **Breakup models (fragment number, area, mass and velocity distributions)**
  - ➢ **Target ranking for active debris removal**

Uncertainty Sources [2]

❑ ***Completely outside the control of modelers***

- **Future launch traffic and space technology evolution**
- **Quality of mitigation measures adopted and overall levels of compliance**
- **Viable technological options for remediation measures with active debris removal**
- **Ill-conceived ASAT tests or other irresponsible deliberate actions endangering the environment**
- **Evolution of solar and geomagnetic activity**
- **Evolution of the upper atmosphere of the Earth at satellite altitudes**

Review of Uncertainty Sources

Trajectory propagators – Collision probability
Initial debris environment

Under the full control of modelers

- Concerning **trajectory propagators** and **collision probability estimation**, in principle there is no intrinsic limitation to reach any appropriate level of accuracy with suitable physical mathematical models, proper software tools and adequate computational resources

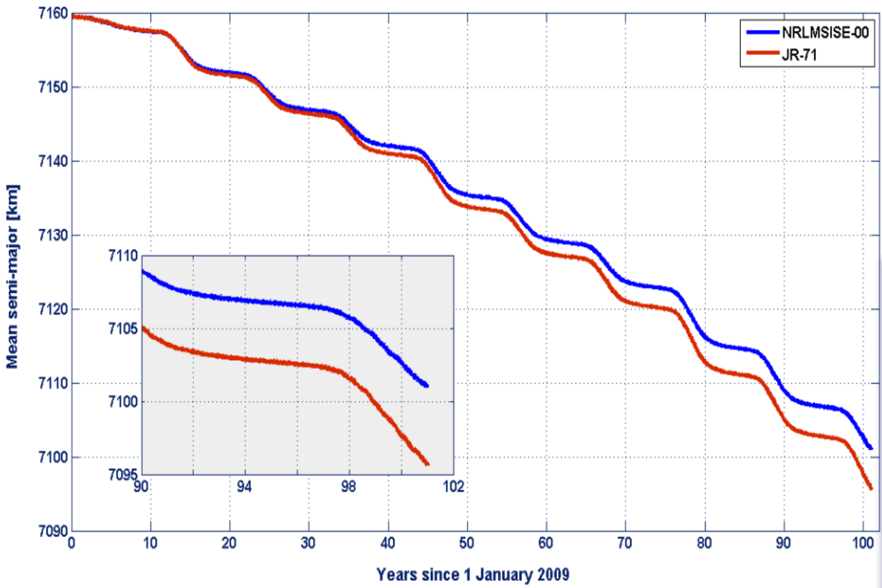
Under the partial control of modelers

- As far as the attention is focused on objects ≥ 10 cm in LEO, i.e. those driving the long-term collisional evolution of the environment, the current catalog is reasonably complete and will be progressively improved in the near future with the coming out of more powerful sensors
- In any case, current state-of-art debris models already take into account the catalog incompleteness, limiting the intrinsic uncertainty of the **initial debris environment** to more than acceptable levels

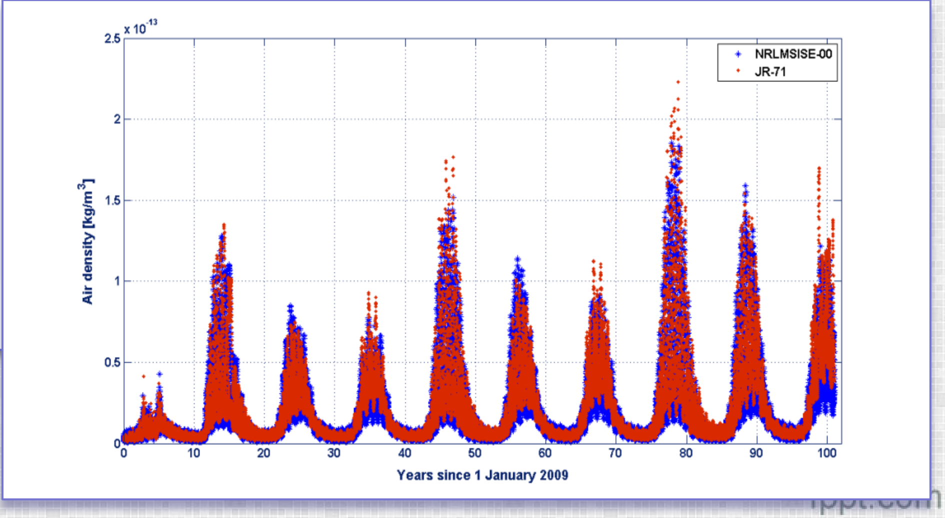
Review of Uncertainty Sources

Atmospheric Density Models

Standard **atmospheric density models** can still be affected by local and short-term inaccuracies of tens per cent, but for long-term propagations they provide a sufficiently good representation of the average thermospheric conditions and do not represent the limiting accuracy factor as far as the drag force modeling is concerned



Long-term propagation of the Envisat semi-major axis with two different atmospheric density models using the same forecasted solar and geomagnetic activities



Atmospheric density at the Envisat altitude calculated with the two models

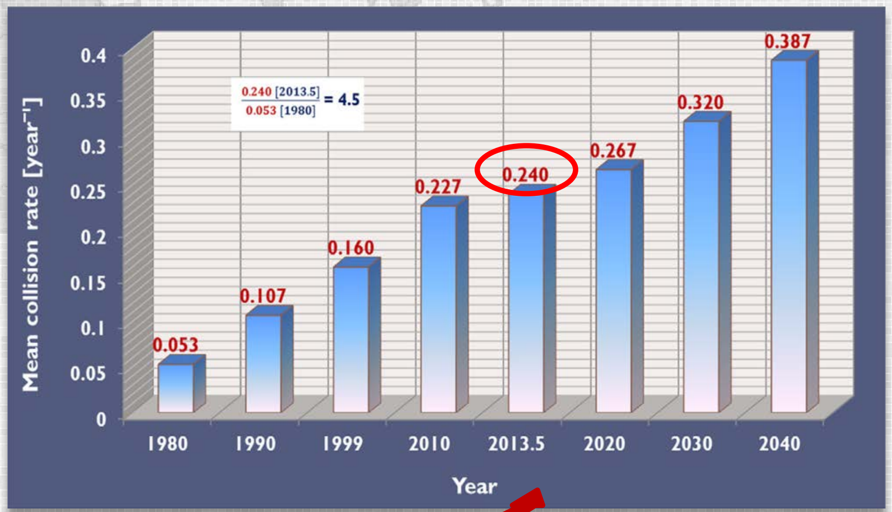
Recorded on-orbit collisions involving catalogued objects

	SOLWIND (1985)	DELTA-180 (1986)	COSMOS 1934 (1991)	CERISE (1996)	THOR BURNER 2A R/B (2005)	FENGYUN-1C (2007)	USA-193 (2008)	COSMOS 2251 IRIDIUM 33 (2009)
OBJECT 1	Solwind P78-1 M_t = 878 kg	Delta-180 2nd stage M_t = 1455 kg	Cosmos 1934 M_t = 800 kg	Cerise M_t = 50 kg	Thor Burner 2A M_t = 50 kg	Fengyun-1C M_t = 880 kg	USA-193 M_t = 1815 kg	Cosmos 2251 M_t = 900 kg
OBJECT 2	Sub-orbital MHV KV M_p = 13.6 kg	USA-19 M_p= 725 kg	Cat. Debris 13475 $M_p \sim$ 0.6 kg	Cat. Debris 18208 $M_p \sim$ 4.5 kg	Cat. Debris 26207 $M_p \sim$ 2.1 kg	Sub-orbital KKV M_p = 600 kg	Sub-orbital LEAP vehicle M_p = 102 kg	Iridium 33 M_p = 560 kg
IMPACT DATE	13 Sep. 1985	5 Sep. 1986	23 Dec. 1991	24 Jul. 1996	17 Jan. 2005	11 Jan. 2007	21 Feb. 2005	10 Feb. 2009
IMPACT ALTITUDE [km]	525	218	980	685	885	863	249	789
IMPACT VELOCITY [km/s]	6.7	2.9	14.3	14.8	5.7	9.4	9.8	11.6
EMR [J/kg] $EMR = \frac{M_p v_{imp}^2}{2M_t}$	3.48×10^5	2.06×10^6	7.67×10^4	9.86×10^6	6.82×10^5	3.01×10^7	2.70×10^6	4.19×10^7
CATALOGUED DEBRIS	285 (~300 debris ≥ 10 cm generated)	16 (~ 800 debris ≥ 10 cm generated)	2	1	6	3391* *30 May 2014	174 (> 800 debris ≥ 10 cm generated)	2227*
CAUSE	Intentional	Intentional	Accidental	Accidental	Accidental	Intentional	Intentional	Accidental

Collisions in orbit

Recorded on-orbit collisions involving catalogued objects	8
Catastrophic collisions according to EMR ≥ 40,000 J/kg	8
Collisions generating > 200 debris ≥ 10 cm	5
Collisions generating < 20 debris ≥ 10 cm	3
Intentional collisions (ASAT tests)	4
Accidental collisions	4
Accidental collisions generating > 200 debris ≥ 10 cm	1
Accidental collisions involving two intact objects	1
Accidental collisions involving a manoeuvrable spacecraft	1

- **Depending on traffic model and mitigation scenarios, in the next century the evolutionary models predict a number of mutual collisions among objects ≥ 10 cm from ~10 (extrapolated traffic, mitigation) to ~70 (increased traffic, no mitigation)**
- **Currently the yearly collision expectancy is ~0.2, i.e. 1 every 5 years, on average**



Review of Uncertainty Sources

Collisional Fragmentation Threshold

- **The energetic threshold EMR for catastrophic collisional breakups is usually assumed to be 40,000 J/kg, based on tests and analyses carried out in the past**

- The actual situation might be more complex, due to basic structural differences between rocket bodies and spacecraft, and among spacecraft as well, with a range of applicable values

- **However, having determined its right order of magnitude, the exact value (or values) of the critical EMR might not be so crucial, in the real world, for the long-term environment evolution in LEO, where the feedback collisions are relevant**

- In fact, looking at the collisions among cataloged objects occurred so far in orbit, the lowest EMR was 90% higher than 40,000 J/kg and the 5 collisions resulting in catastrophic fragmentations had EMRs from 1 to 3 orders of magnitude higher

Review of Uncertainty Sources

Collisional Fragmentation Threshold (cont.)

- **The problem is the implementation of the threshold in the evolutionary models if the impact geometry is ignored**

- Only 1 out of 4 accidental collisions recorded so far with EMR > 40,000 J/kg resulted in a catastrophic breakup

- According to the NASA standard breakup model

$$N(L_C) = 0.1\, M^{0.75} L_C^{-1.71}$$

- Catastrophic collision (EMR > 40,000 J/kg)

$$M = M_t + M_p$$

- Non-catastrophic collision (EMR < 40,000 J/kg)

$$M[kg] = M_p\,[kg] \cdot (v_{imp}[km/s]/1\,[km/s])^2$$

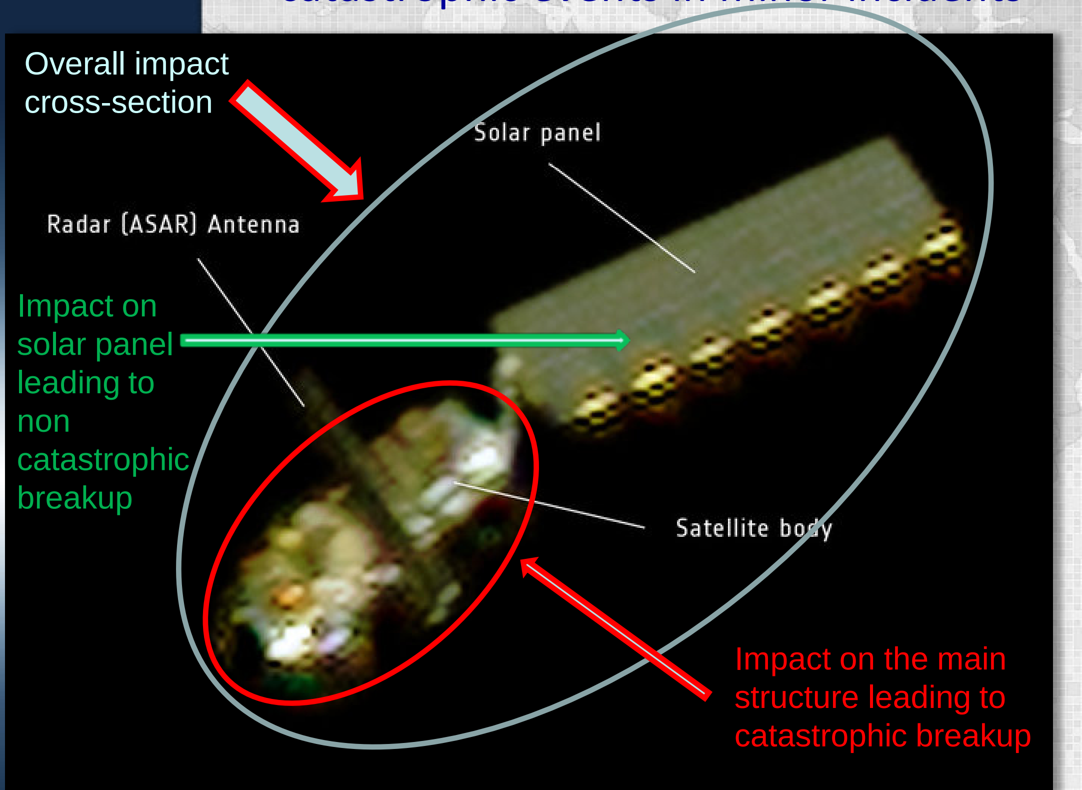
the 3 “missed” events, which in total produced only 9 cataloged fragments, would have produced

- EMR > 40,000 J/kg ⟶ **974 debris ≥ 10 cm**
- EMR < 40,000 J/kg ⟶ **391 – 1213 debris ≥ 10 cm**, depending on the formula implementation (conservation of the mass or not)

Review of Uncertainty Sources

Collision Geometry

- **The on-orbit collisional record suggests that collision geometry may be much more important than the fragmentation threshold in determining a catastrophic breakup**
- Object shapes, with loose structures or appendages, like solar panels, antennae and booms, play probably a critical role, often transforming potentially catastrophic events in minor incidents



Overall impact cross-section

Impact on solar panel leading to non catastrophic breakup

Impact on the main structure leading to catastrophic breakup

Envisat as seen by Pleiades (courtesy of CNES)

- The critical impact cross section leading to catastrophic collisions, in particular during the debris-intact events, might be significantly smaller than the overall impact cross section, possibly by more than a factor of 2
- This might also be true for the intact-intact events, even though the average scaling factors would probably be smaller

Review of Uncertainty Sources

Consequences of Collision Geometry

- **Even if the expected number of collisions among objects larger than 10 cm were correctly estimated, the oversight of collision geometry might lead to a significant overestimation in the expected number of catastrophic breakups**

- Since catastrophic collision fragments act as feedback impactors, leading to further catastrophic collisions and dominating, after a few decades, the evolution of the environment, any uncertainty in the expected number of catastrophic collisions in LEO has important consequences on long-term environment predictions

- Even limiting the consequences of collision geometry to debris-intact events, after one century a reduction of breakup fragments by tens per cent should be expected

- **A statistically improved knowledge of the relationship between <u>overall impact cross section</u> and <u>critical cross section</u> for catastrophic collisions would be therefore of paramount importance**

Review of Uncertainty Sources

Breakup Models

- **Currently the common (and best) choice is represented by the NASA standard breakup model** (*if correctly implemented*)
- It was empirically developed from 1980’s on-orbit satellite breakups and the Satellite Orbital Debris Characterization Impact Test (SOCIT) series, carried out on the ground in early 1990’s
- Its release represented a major progress in the modeling field
- Considering the changes in spacecraft design and materials introduced since the 1990’s, it should not be surprising if its predictions were not in strict agreement with the debris size and A/M distributions generated by some on-orbit catastrophic collisions
- The analyses carried out by NASA comparing the model with on-orbit collisional breakups showed the slope of the cumulative size distribution for debris larger than a few millimeters was in reasonable agreement with the available observations
- Concerning the number of debris $\geq$ 10 cm, underestimations or overestimations by a factor of 2 were possible, on a case by case basis
- The modeled distributions were sometimes deficient in high A/M debris

Review of Uncertainty Sources

Target Ranking for Active Removal

- **The potential long-term benefits of active debris removal should depend on the order in which the abandoned objects are taken away from the sensitive orbital regions**
- Generally target ranking lists are obtained by adopting a priori heuristic approaches
- For instance, using a ranking scheme devised in 2013, we found that the removal of the 25 most massive objects abandoned in sun-synchronous orbits, between 700 and 1100 km, was equivalent to that of more than 400 average intact bodies (of 934 kg) placed into the same orbit of Envisat
- **However, different ranking schemes based on equally reasonable assumptions may produce quite different priority lists and it is not straightforward to check a priori their relative long-term effectiveness, even disregarding the intrinsic stochastic nature of the debris environment long-term evolution**

Review of Uncertainty Sources

Traffic Models

Future launch traffic and space technology evolution

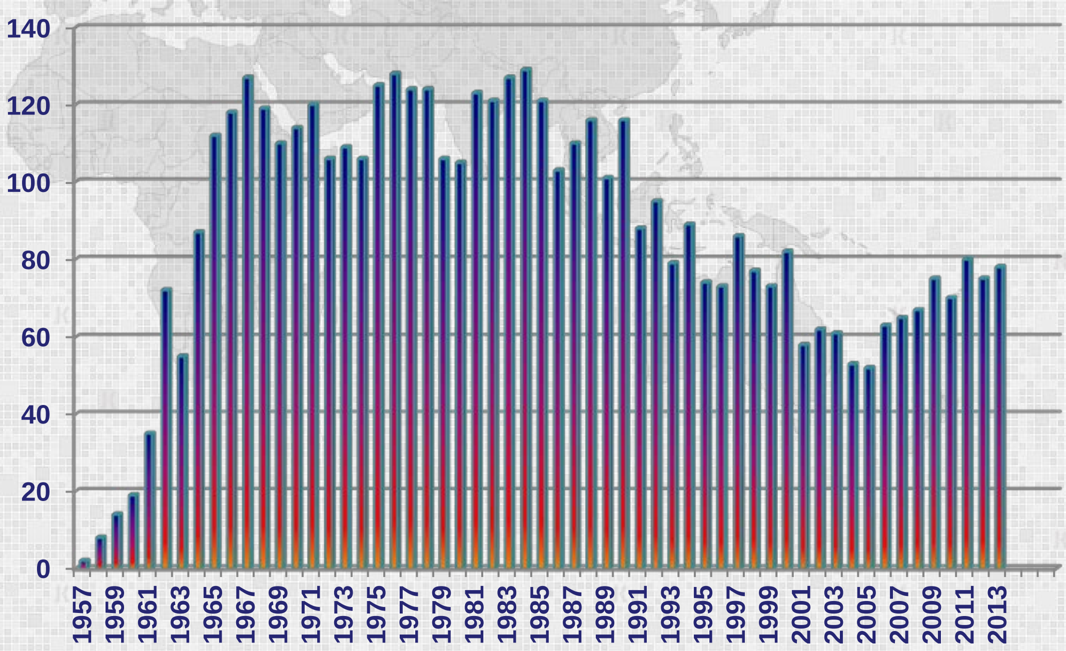
can be reasonably assessed for no more than 20-30 years and depend on socio-economical, geopolitical and technological processes which nobody can control or predict in the long-term with an assigned confidence level; as in history, only the past can be analyzed and explained, but no reliable extrapolations to the (far) future are possible

Launches in orbit (1957-2013): 5016

- The yearly number of launches was quite variable, reflecting the above mentioned motivations
- However, the net yearly number of objects added to circumterrestrial space can be rather accurately fitted with linear trends

Average yearly number of objects added to space

68	Payloads
8	Payloads mission related objects
33	Rocket bodies
14	Rocket bodies mission related objects



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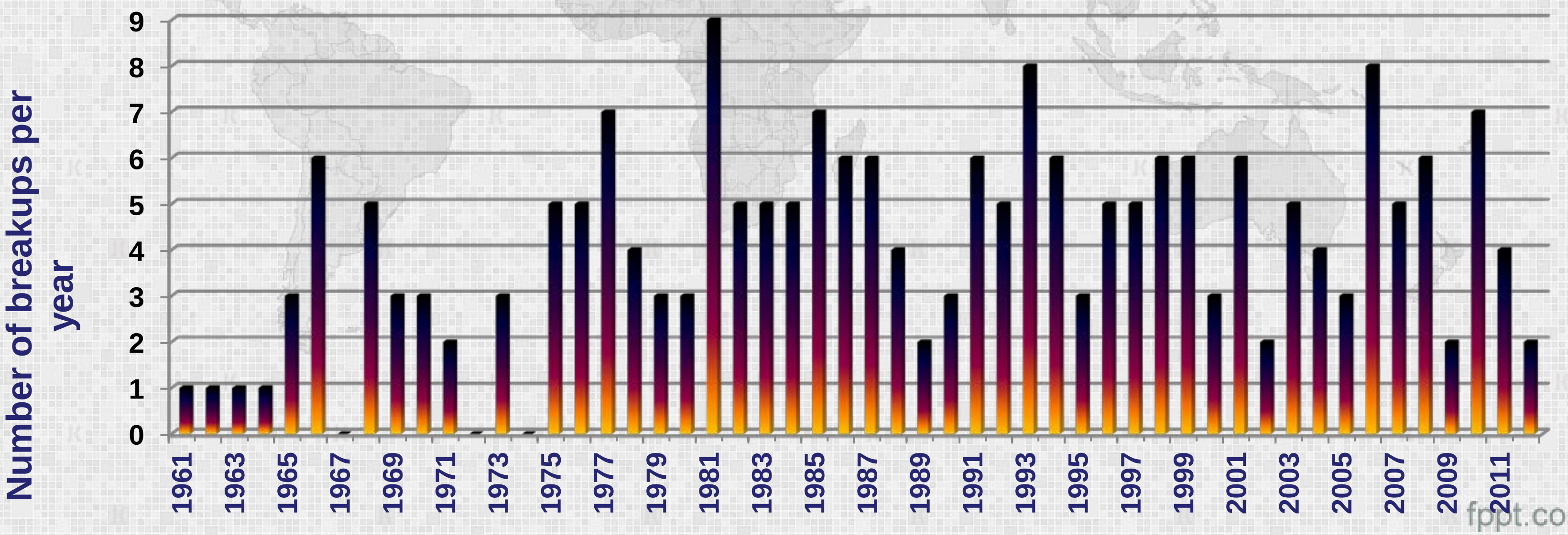
Mitigation Measures

- **Quality of mitigation measures adopted and overall levels of compliance**

are depending on national/international laws, guidelines and standards, in addition to socio-economical, geopolitical and technological factors

- Currently about 2/3 of the GEO spacecraft are re-orbited at the end-of-life according to the IADC Space Debris Mitigation Guidelines
- Approximately 60% of spacecraft and upper stages are compliant with the 25-year residual lifetime rule in LEO
- 2-3 non collisional breakups per year of spacecraft and rocket bodies still occur, on average



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Other Anthropogenic Variables

- **Viable options for remediation measures with active debris removal**

  depend on

  - National/international laws
  - Target ranking criteria
  - Perceived short and long-term cost/benefit ratio
  - Available technological solutions and political will, coupled with broader socio-economical and geopolitical aspects

- **Ill-conceived ASAT tests or other irresponsible deliberate actions endangering the environment**

  depend on

  - Unpredictable human behaviors
  - Motivations, errors or misjudgments (for instance, the Fengyun-1C intentional destruction alone increased the number of cataloged debris by the same amount accumulated during the previous 20 years of global space activity, including failures and accidental breakups)

Review of Uncertainty Sources

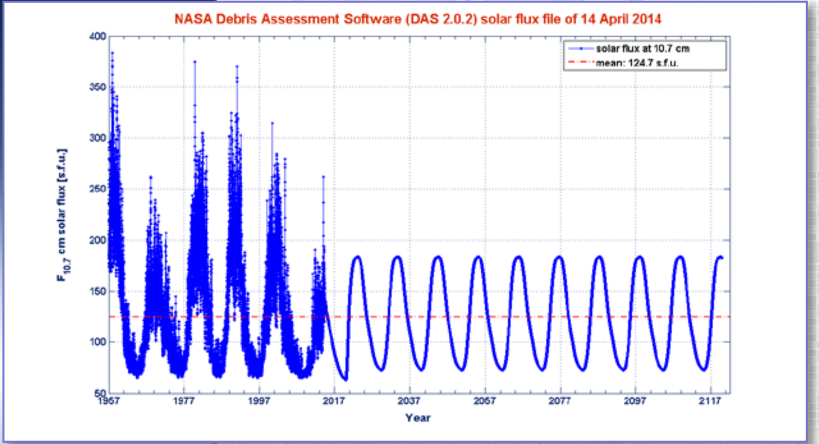
Evolution of the Upper Atmosphere

- **Evolution of solar and geomagnetic activity**

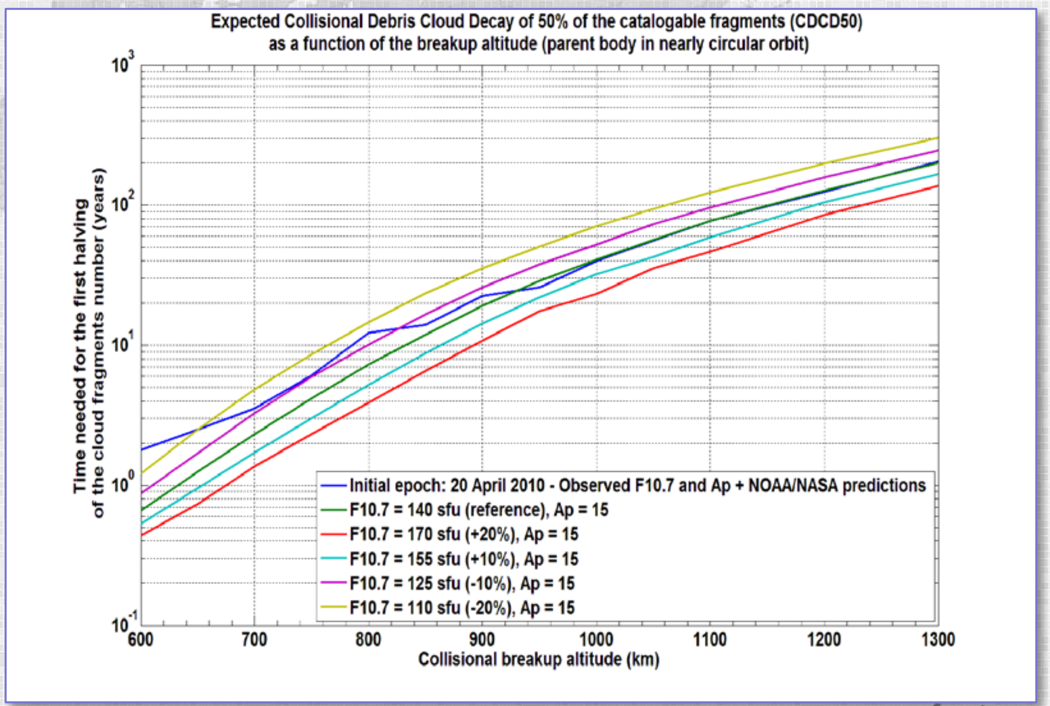
  cannot be reliably predicted more than 1 solar cycle (~11 years) in advance, governed as it is by very complex and still not fully understood natural phenomena

- **Evolution of the upper atmosphere of the Earth at satellite altitudes**

  depends on intricate and still not fully understood natural phenomena (e.g. during the last very long and deep solar activity cycle minimum)


NASA Debris Assessment Software (DAS 2.0.2) solar flux file of 14 April 2014

- **The first halving time (*CDCD50*) of a collisional debris cloud is strongly affected by solar activity**
- **As an example, at 900 km, an average increase or decrease of $F_{10.7}$ by 20% can result in a *CDCD50* decrease or increase by a factor of 2**


Expected Collisional Debris Cloud Decay of 50% of the catalogable fragments (CDCD50) as a function of the breakup altitude (parent body in nearly circular orbit)

Conclusions

- The long-term predictions uncertainties affecting the debris environment are depending on a number of assumptions on which the modelers have only partial or no control at all
- Any change in this set of hypotheses might have significant consequences on the time scale of debris growth
- One critical area where improvements will be possible in the future concerns a more in depth understanding of the difference between the target critical area leading to a catastrophic breakup and the overall cross-section, including loose structures or appendages, irrespective of the fragmentation energy threshold
- The current renewed interest in satellite breakup tests carried out on the ground is motivated by the perceived need to further enhance the reliability of breakup models, so this is another field in which important progresses should be expected
- However, there are relevant natural and anthropogenic variables which cannot be reliably predicted beyond a few decades in the future, so appropriate ways to include them in the uncertainty budget must be found