Order of Magnitude Analysis for On-ground Risk from Uncontrolled Re-entries

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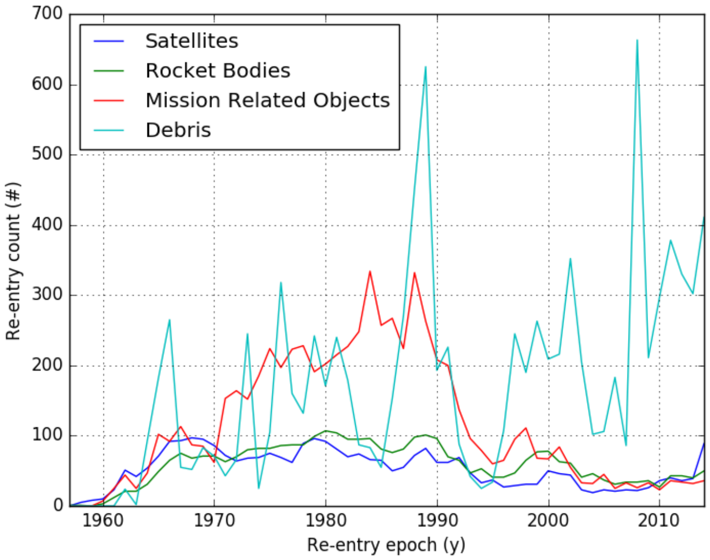
Outline

- Many of the CleanSat Building Blocks focus on increasing the ‘demisability’ of a satellite during re-entry.
    - Before CleanSpace, this was mostly an academic exercise.
    - It illustrates the difficult road towards real-world verification.
    - It illustrates the difficult road towards simulated verification.

- The need for ‘demisability’ comes from the need to limit the casualty risk to 1 in 10 000 per re-entry event.
    - One of the last ‘old’ requirements to be banished from the waiver regime.
    - What does it imply for everyday life on Earth?

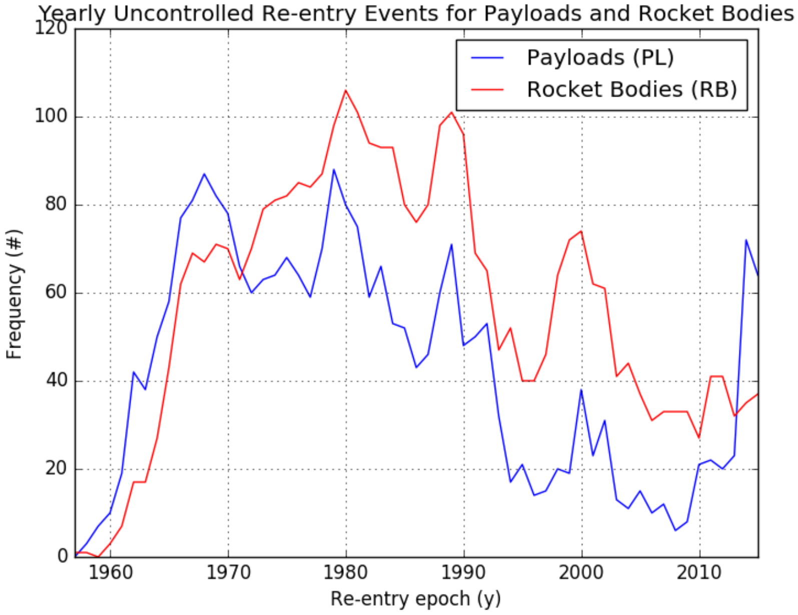
Historical re-entries in numbers

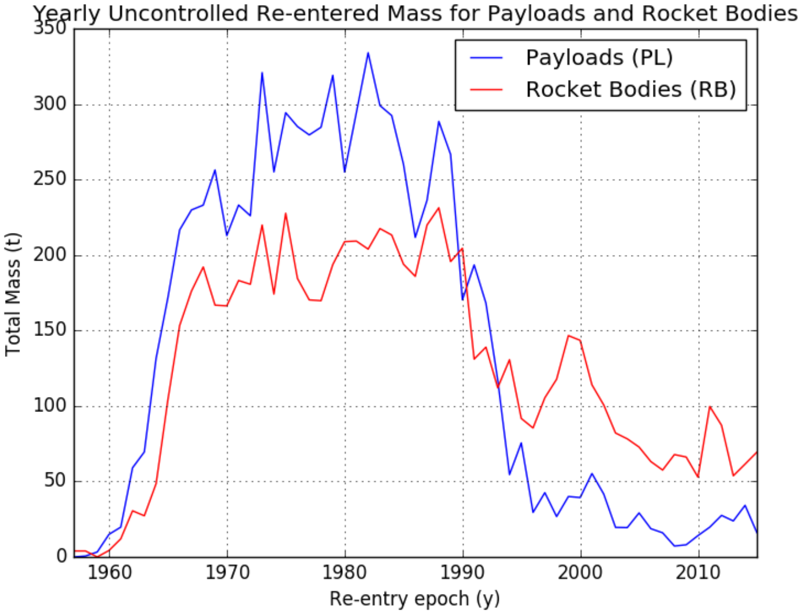
- Since 1957, ~ 41 500 ton worth of objects have been put into space over 5197 launches.
- ~ 33 200 ton came down, with most of it to human spaceflight activities.
- At least 23635 re-entry events.
- 43% Debris, 32% MRO, 25% PL/RB
- Most of them came down uncontrolled.



Historical re-entries in numbers

- For the total on-ground risk assessment we focus on the 5876 PL/RB, covering ~ 15 700 ton.





Historical re-entries in numbers

Object	Agency (Country)	Re-entry Mass (kg)	Decay Epoch	Type
MIR	ROSCOSMOS (Russia)	120,000	23-Mar-2011	Controlled
Columbia (STS-107)	NASA (USA)	82,000	1-Feb-2003	Uncontrolled
Skylab	NASA (USA)	74,000	11-Jul-1979	Semi-Controlled
Salyut 7 / Cosmos 1686	ROSCOSMOS (Russia)	40,000	7-Feb-1991	Semi-Controlled
Salyut 6 / Cosmos 1267	ROSCOSMOS (Russia)	34,000	29-Jul-1982	Controlled
Cosmos 1870	ROSCOSMOS (Russia)	20,000	29-Jul-1989	Controlled
Cosmos 929	ROSCOSMOS (Russia)	19,800	2-Feb-1978	Controlled
Cosmos 1443	ROSCOSMOS (Russia)	19,800	19-Sep-1983	Controlled
Salyut 5	ROSCOSMOS (Russia)	18,800	8-Aug-1977	Controlled
Salyut 4	ROSCOSMOS (Russia)	18,700	2-Feb-1977	Controlled
Almaz 1	ROSCOSMOS (Russia)	18,550	17-Oct-1992	Controlled
Salyut 1	ROSCOSMOS (Russia)	18,300	11-Oct-1971	Controlled
Salyut 2	ROSCOSMOS (Russia)	18,300	28-May-1975	Uncontrolled
Salyut 3	ROSCOSMOS (Russia)	18,300	24-Jan-1975	Controlled
Cosmos 557	ROSCOSMOS (Russia)	18,300	22-May-1973	Uncontrolled
Apollo 5 Nose Cone	NASA (USA)	17,100	30-Apr-1966	Uncontrolled
Apollo 6 CSM BP-13	NASA (USA)	16,900	1-Jul-1964	Uncontrolled
Apollo 7 CSM BP-15	NASA (USA)	16,700	22-Sep-1964	Uncontrolled
Apollo 10 CSM BP-9	NASA (USA)	16,700	22-Nov-1975	Uncontrolled
Apollo 9 CSM BP-16	NASA (USA)	16,700	10-Jul-1985	Uncontrolled
Apollo 8 CSM BP-26	NASA (USA)	16,700	8-Jul-1989	Uncontrolled
ATV-4	ESA	15,750	2-Nov-2013	Controlled
CGRO	NASA (USA)	14,910	4-Jun-2000	Controlled

Casualty risk requirements

- ISO-24113 (ECSS-U-AS-10C):

6.3.4 Re-entry

6.3.4.1 For the re-entry of a spacecraft or launch vehicle orbital stage (or any part thereof), the maximum acceptable casualty risk shall be set in accordance with norms issued by approving agents.

- ADMIN-IPOL-2014-002e:

b) For ESA Space Systems for which the System Requirements Review has not yet been kicked off at the time of entry into force of this Instruction, the casualty risk shall not exceed 1 in 10,000 for any re-entry event (controlled or uncontrolled). If the predicted casualty risk for an uncontrolled re-entry exceeds this value, an uncontrolled re-entry is not allowed and a targeted controlled re-entry shall be performed in order not to exceed a risk level of 1 in 10,000.

- ESSB-HB-U-002:

4.19.1 Rationale for the requirement

This requirement addresses with a maximum risk figure each spacecraft, launch vehicle stage, and MRO, which can re-enter in controlled or uncontrolled way. ESA as “approving agent” has set the maximum acceptable casualty risk of 10^{-4} (computed as casualty expectancy) for each re-entry event of space systems procured under ESA Programmes, including spacecraft, launch vehicles stages, inhabited or robotic vehicles ([RD1]).

Casualty risk from uncontrolled re-entries

- ESA perspective on casualty/fatality risks:

Casualty expectancy **Fatality expectancy**

$$E_{f,i} = \sum_{n} \sum_{m} (P_i)_{n,m} \cdot (\rho_p)_{n,m} \cdot (A_C)_{n,m} \cdot (\eta_f)_{n,m}$$

Bins on Earth surface

Impact probability

Population density

Casualty cross-section

Fatality index

- Similar definitions are in use around the globe:
  - NASA, JAXA, France LOS (casualty expectancy vis-à-vis casualty probability),
  - The value 1 in 10 000 original came from aviation safety (actually times 100),
  - Keeping the terms ‘simple’ enables comparison and understandable verification.

Casualty risk from uncontrolled re-entries

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Bins on Earth surface

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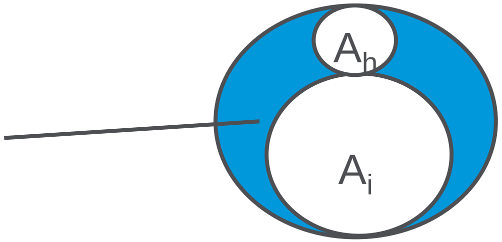
Fatality index

- (Straightforward) ways for risk reductions:
  - Stay away from populated regions, i.e. controlled re-entries,
  - Limit the debris generations, i.e. design for demise,
  - Question the calculation of the contributing terms.

Casualty risk from uncontrolled re-entries

- Casualty area:

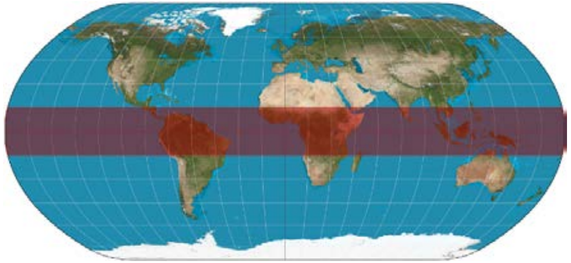
$$A_C = \left(\sqrt{A_h} + \sqrt{A_i}\right)^2$$

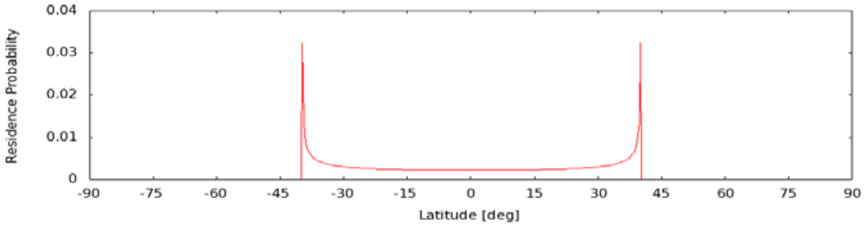


- A_c union of a human A_h, $0.36 m^2$, and the fragment A_i.
    - The fragment area is computed as the average projected area of the fragment.
    - Isn't this an over estimation? Yes, worst-case principle (human lying down).
    - Why not consider shielding? No reliable data source, nor studies on the effects.
    - What about re-entry attitudes? Extremely difficult the compute with confidence.

Uncontrolled re-entry risk: Location

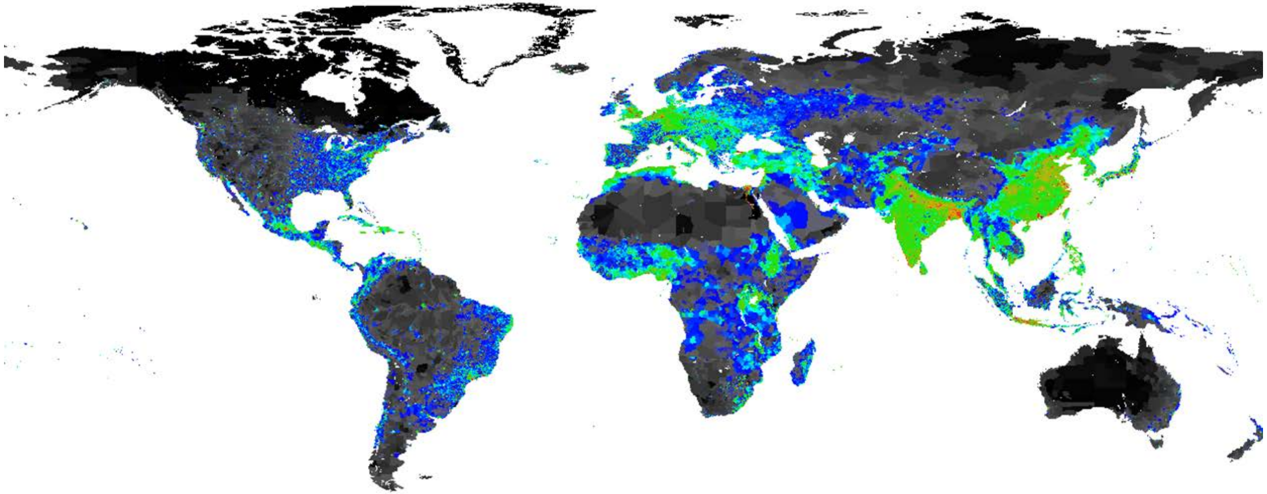
- Circular re-entry:
  - Re-entry driven by atmospheric drag.
  - Circularisation due to higher drag at perigee before re-entry.
  - Possible re-entry location in symmetric latitude band defined by the inclination.





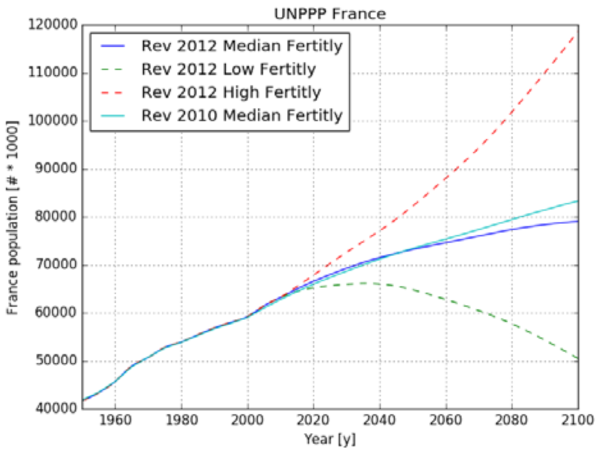
Uncontrolled re-entries risk: Human Population

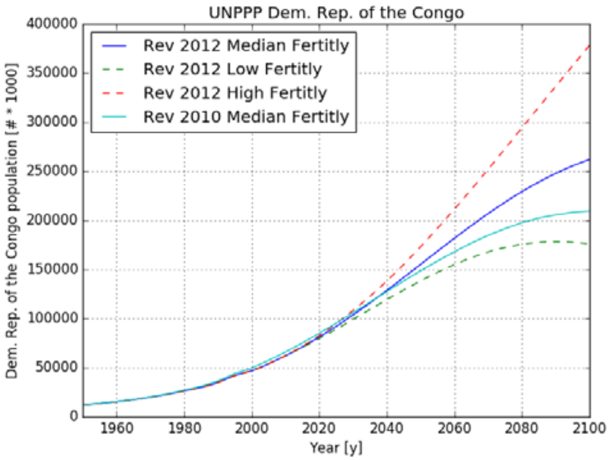
- Gridded Population of the World v4 (2015)

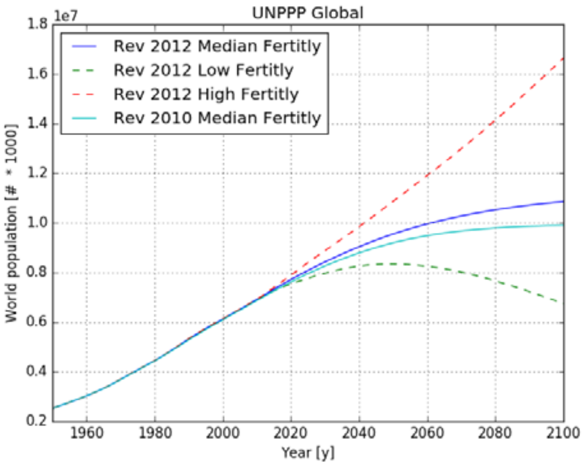


Uncontrolled re-entries risk: Human Population

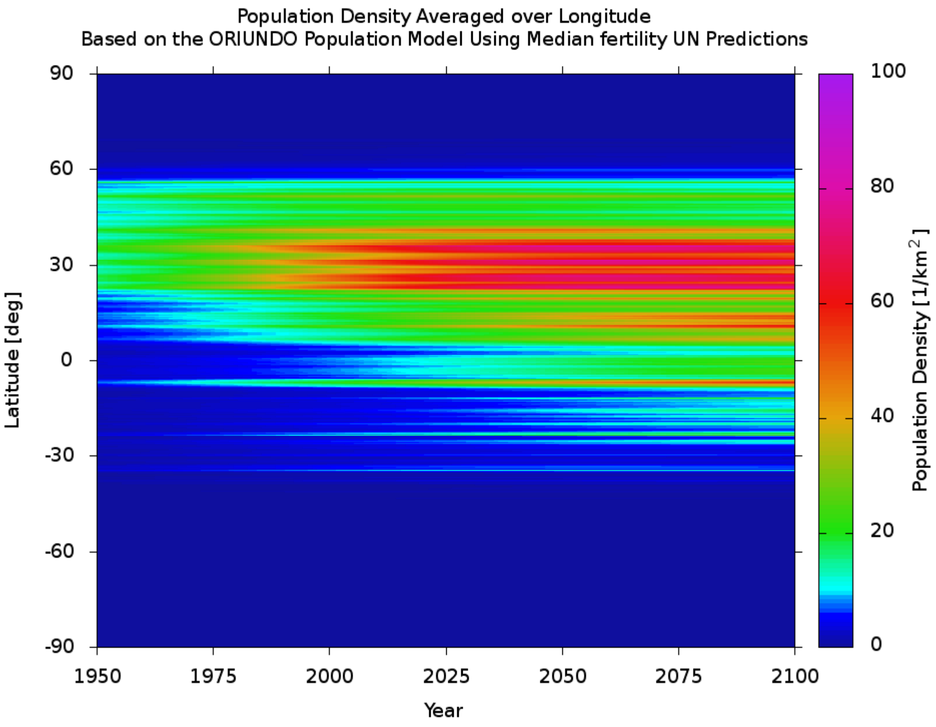
- United Nation Probabilistic Population Projections:
  - Based on country/region-wise fertility, mortality, and migration
  - The median model is adopted, and risk calculations have to account for regional differences.

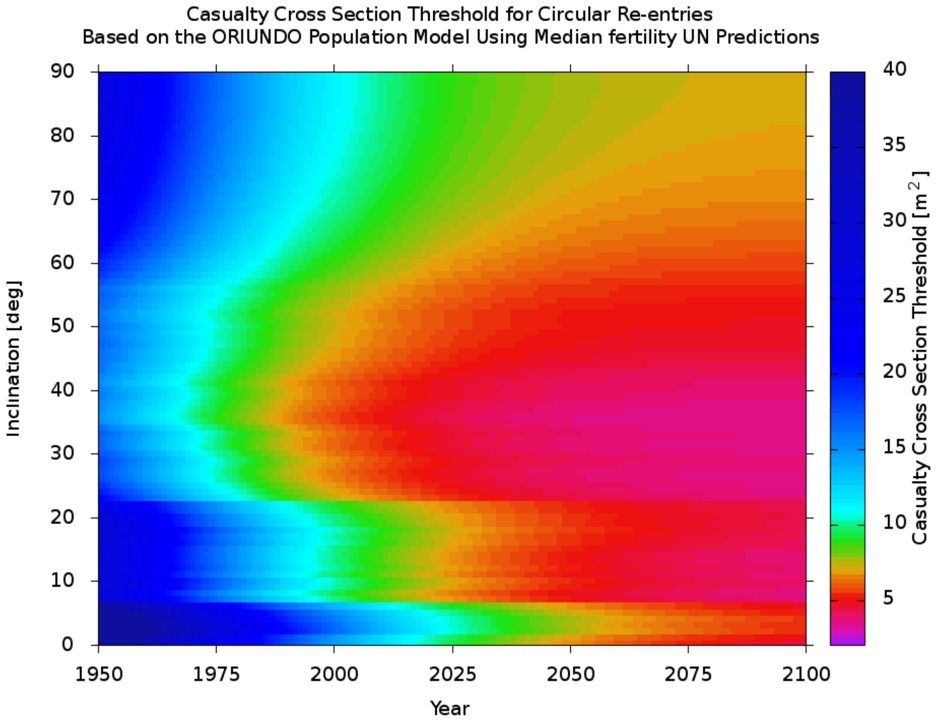




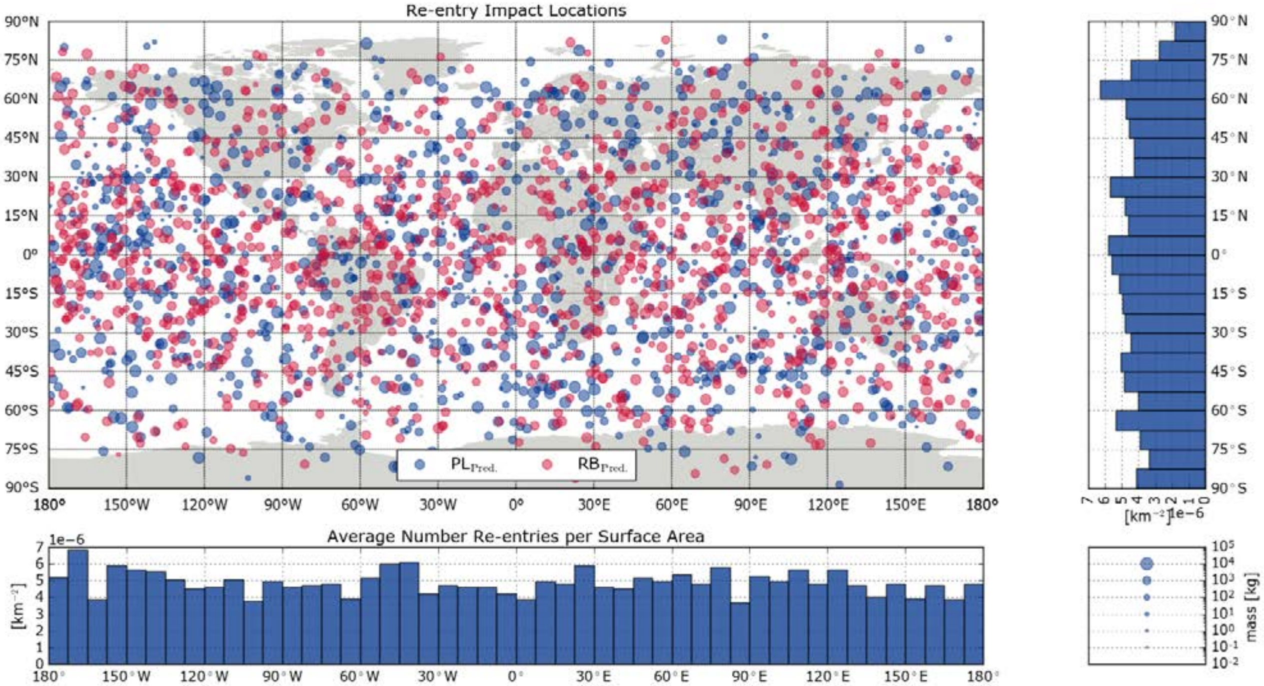


Uncontrolled re-entries risk: Casualty Area Threshold

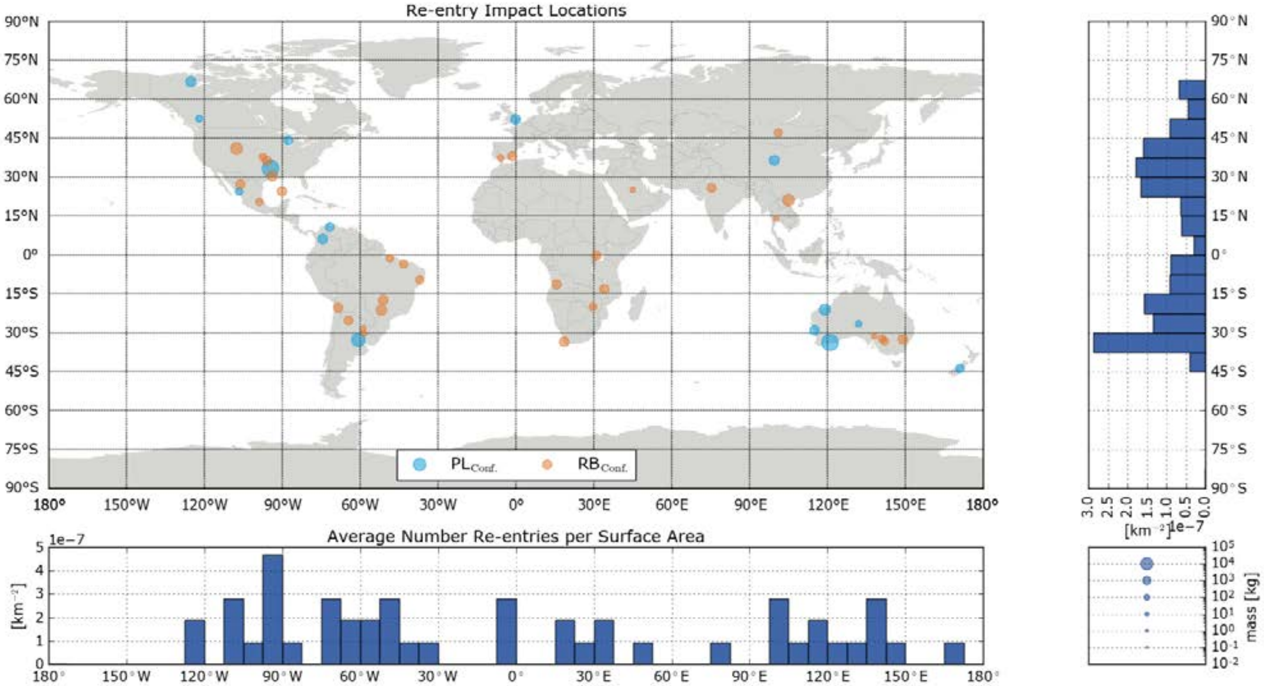




Uncontrolled re-entries risk: Casualty Area



Uncontrolled re-entries risk: Casualty Area



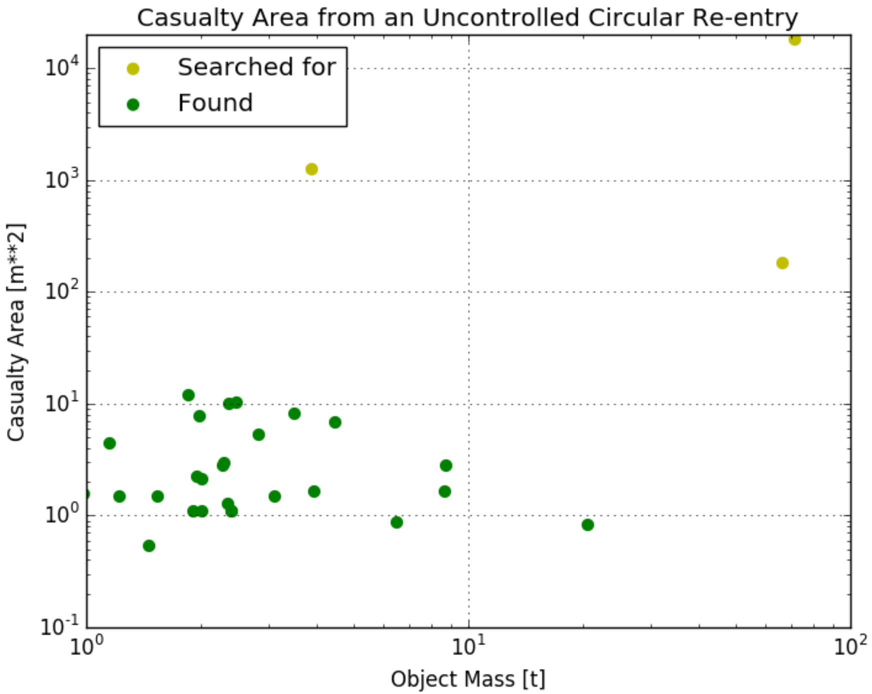
Uncontrolled re-entries risk: Casualty Area

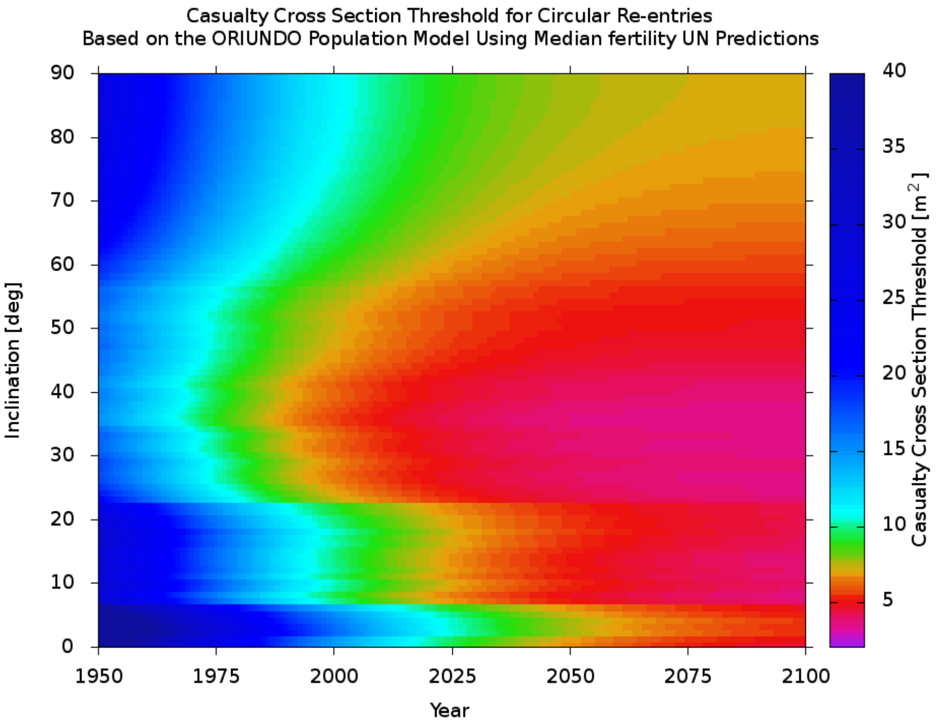
- The minimalist approach to compute A_c : Only fragments found on ground are representative as a casualty area estimator.
  - More than 70 re-entry events involving recovered on-ground (> 50% were rocket bodies), but only 50 can be linked to source objects with some certainty.
  - Most often pressure vessels (about 60) and unidentifiable metal shrapnel found.
  - The Delta-II second stage and PAM-D duo is the most identified source of re-entry debris (respectively 4 and 5 times).

Uncontrolled re-entries risk: Casualty Area

- The minimalist approach to compute A_c : Only fragments found on ground are representative as a casualty area estimator.
    - Space Shuttle Columbia (2003, USA), 50000+ fragments
    - Skylab (1979, Australia), 500 fragments (failed semi-controlled re-entry)
    - Cosmos 945 (1978, Canada), Radioactive, 3500 fragments, over 65 kg including 47 Beryllium rods.

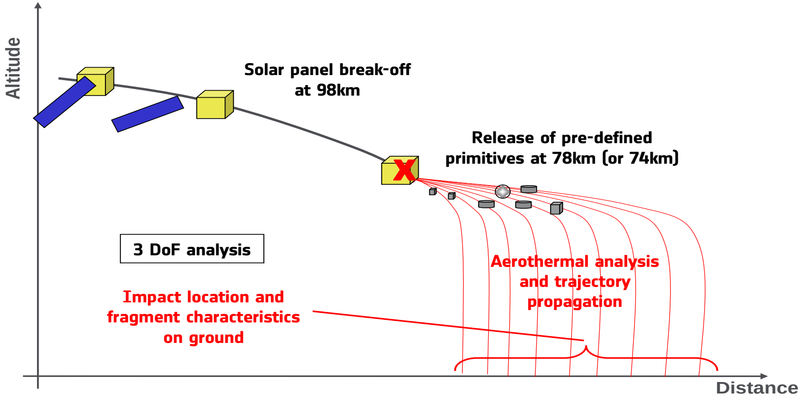
Uncontrolled re-entries risk: Casualty Area





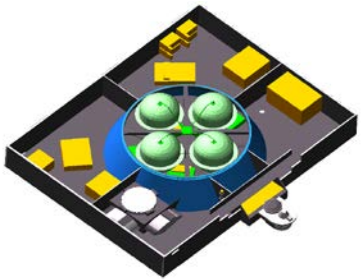
Uncontrolled re-entries risk: Casualty Area

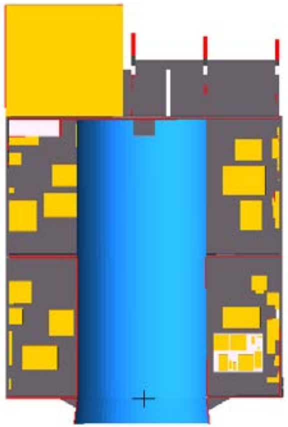
- The object oriented (OO) approach to compute A_c: The objects are modelled as geometric primitives and settings are rigidly defined for the purposed of verification.
  - 3 DoF propagation
  - Averaged thermal analysis
  - Fixed input conditions derived from experiment



Uncontrolled re-entries risk: Casualty Area

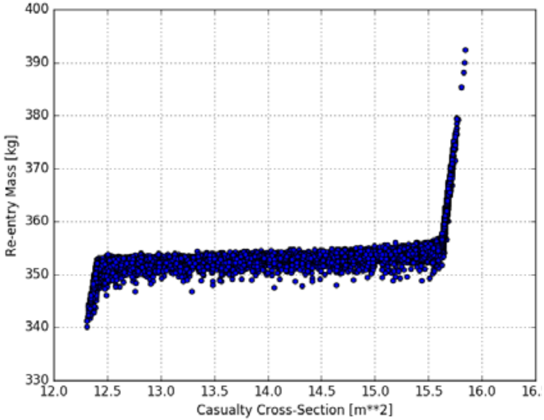
- The spacecraft oriented (SO) approach to compute A_c: The objects are modelled as finite volumes to enable 3D thermal and structural analysis:
    - 6 DoF motion propagation.
    - No user defined break-up conditions
    - Still only a (coarse) approximation for CFD calculations
    - Aimed at removing the limitations of OO.

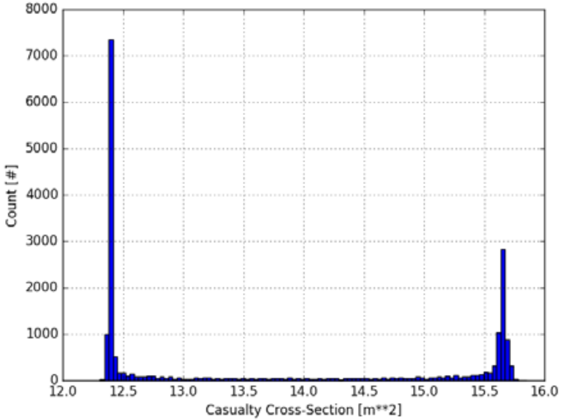


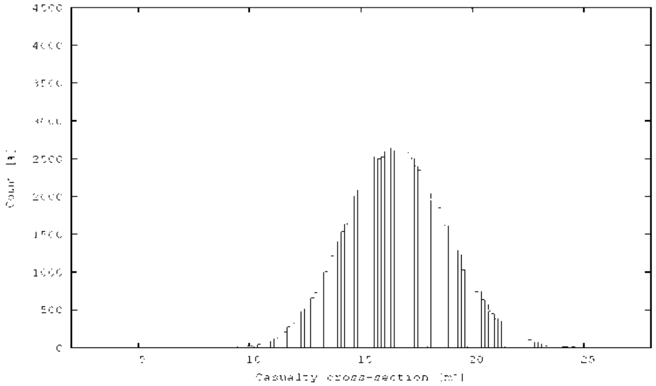


Uncontrolled re-entries risk: Casualty Area

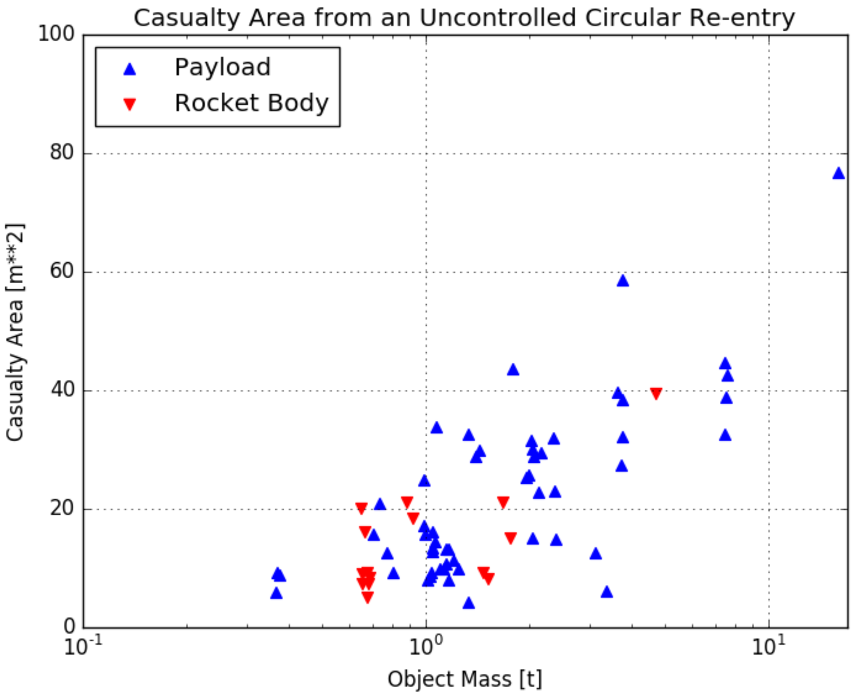
- OO per definition hides away the underlying uncertainties of the re-entry process, making it difficult (not impossible) to use them as engineering tools.
- SO alleviates the OO issues from a research point of view, but is not (yet) in a position to derive stochastic conclusions.
- The desirable agreement between OO and SO is lost in the stochastic domain.

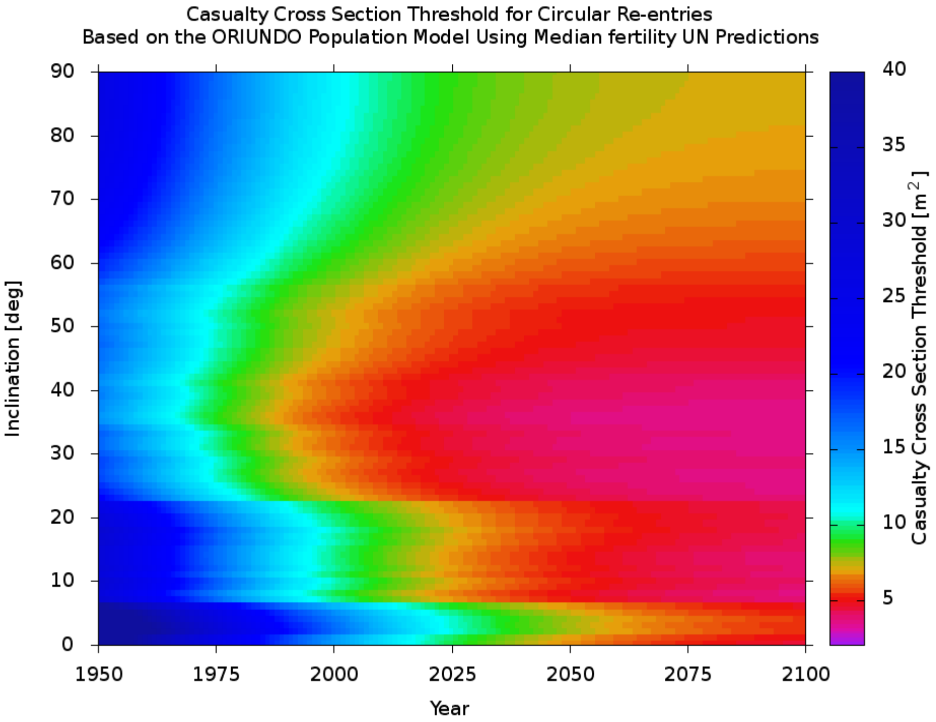




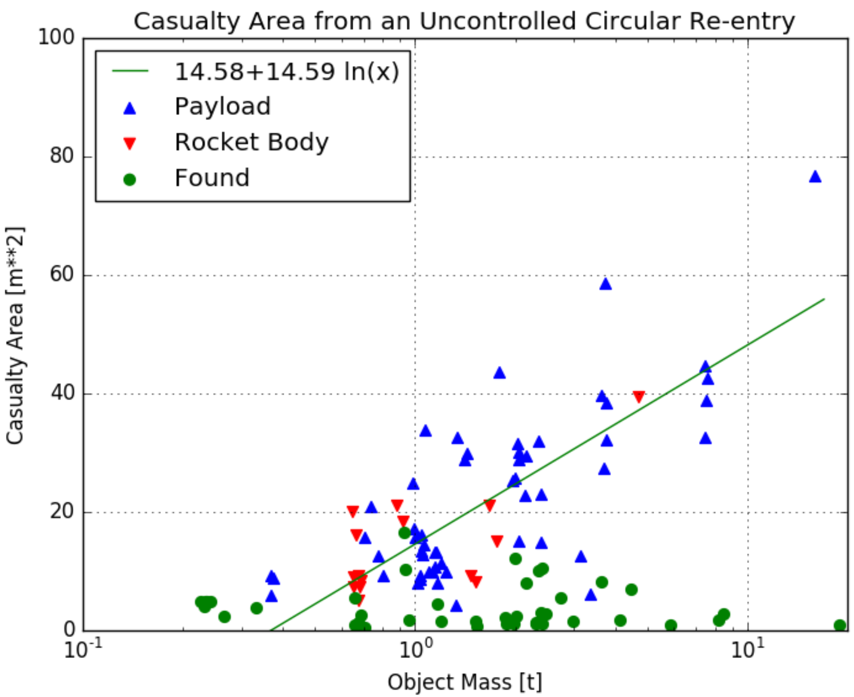


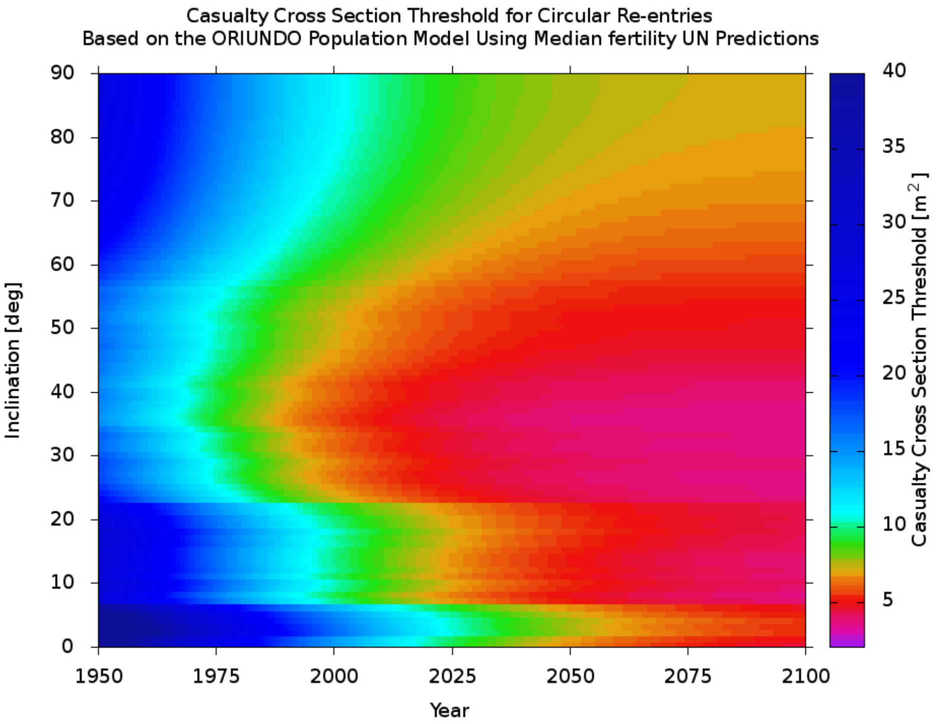
Uncontrolled re-entries risk: Casualty Area



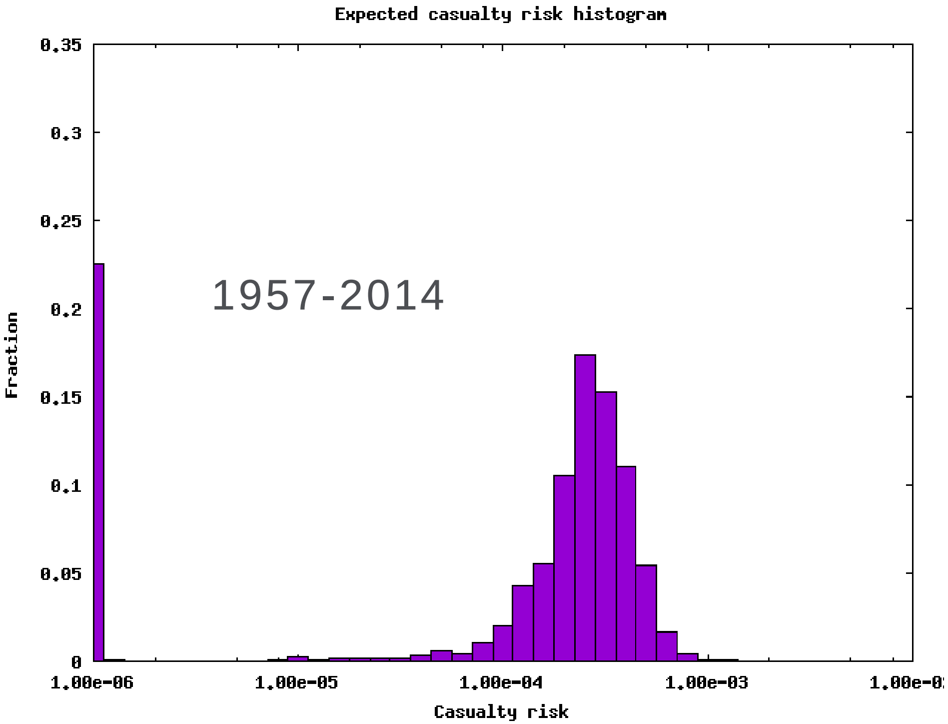


Uncontrolled re-entries risk: Casualty Area





Historical re-entries in risk figures



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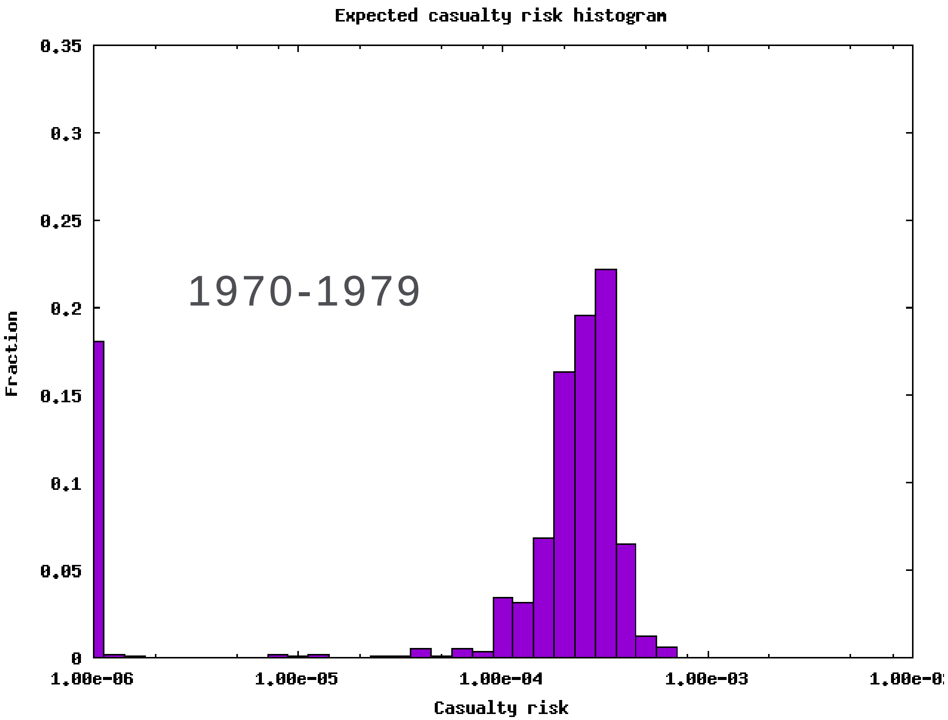

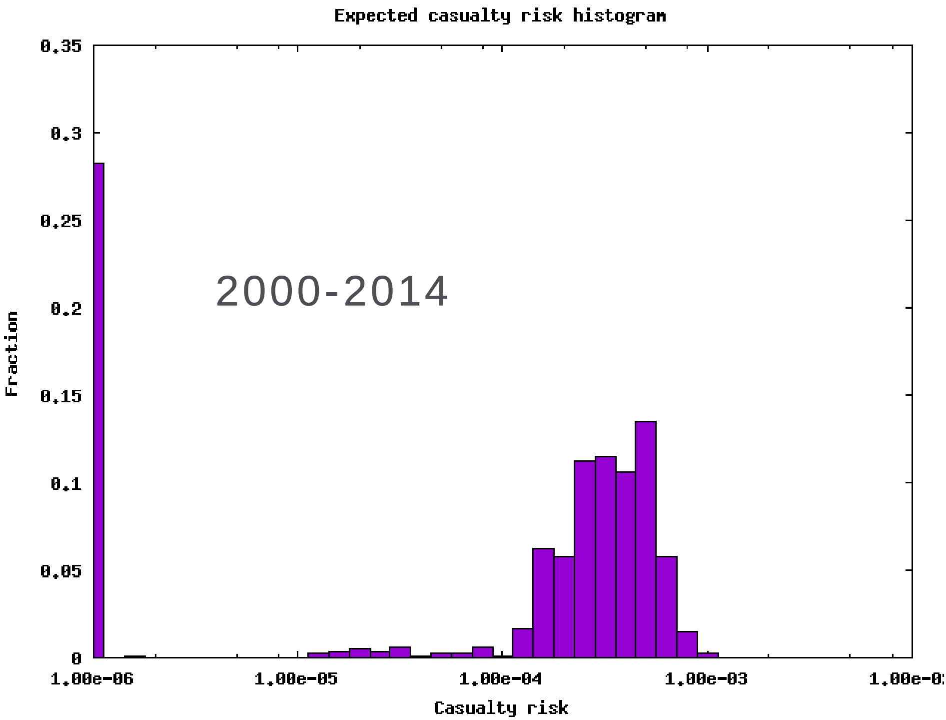

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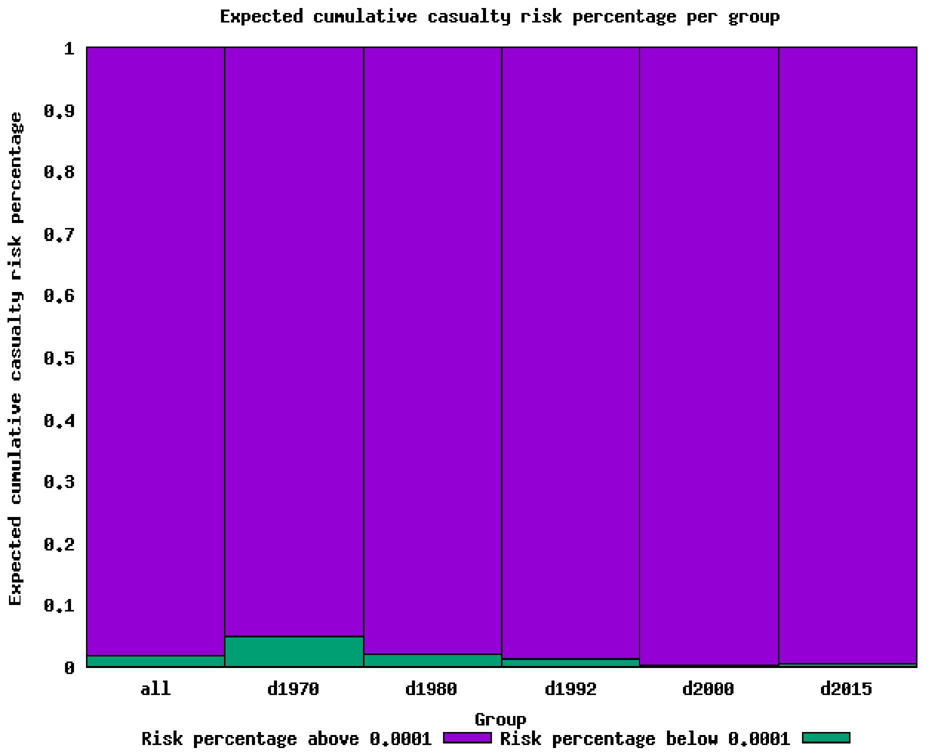
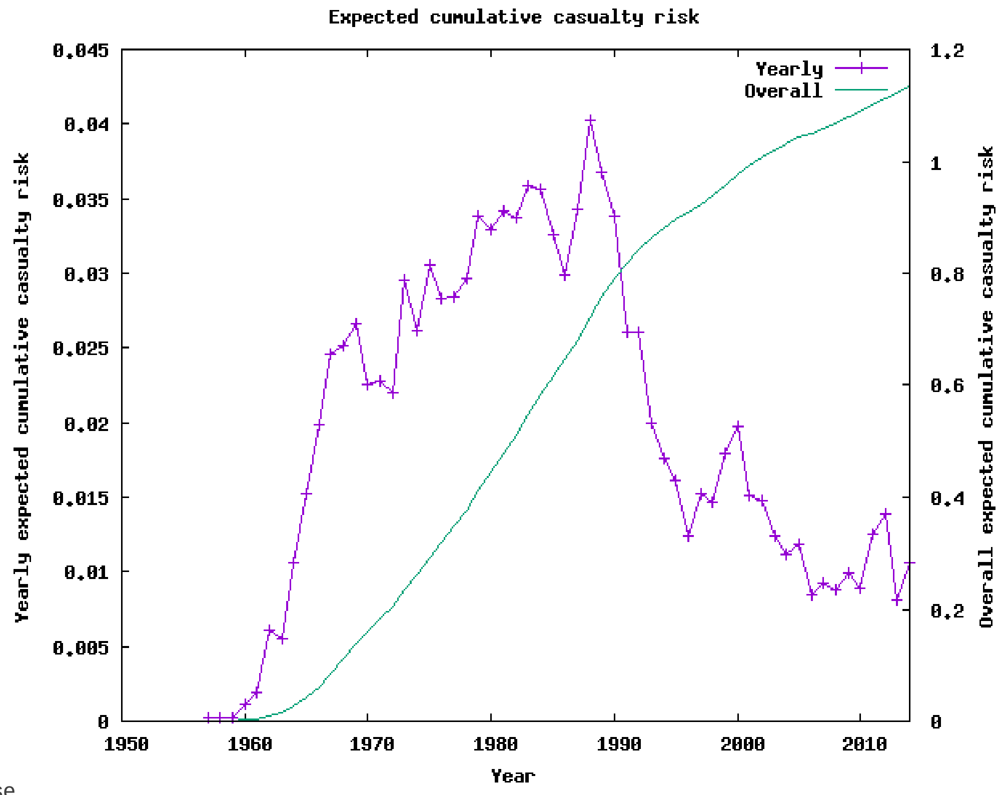
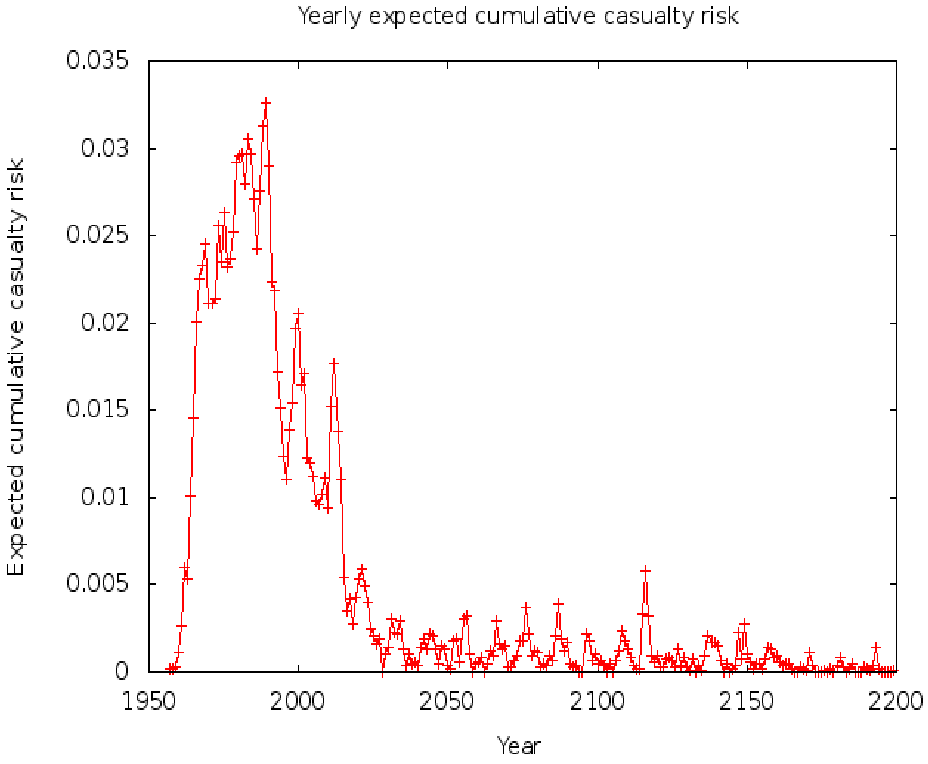


Historical re-entries in risk figures



Future re-entries in risk figures



- We can’t change the past risks we have taken, but technically ADR can modulate future risk due to uncontrolled re-entries.

- New launches, adhering to the 25 year orbital lifetime rule, will create a new ‘bulge’ if D4D is not implemented.

Historical re-entries in risk figures

- Risk perception is a key issue for spaceflight.
- Annual personal risk of fatality due to common causes and activities (based on 1995 data).

Activity	Personal risk of fatality	
Coal mining	9.3×10^{-3}	1/107
Cancer	1.8×10^{-3}	1/545
Fire fighting	8.0×10^{-4}	1/1250
Motor vehicle operation	2.2×10^{-4}	1/4500
Home accidents	1.2×10^{-5}	1/83000
Air travel	2.0×10^{-6}	1/500000
Lightning	5.0×10^{-7}	1/2000000
Space object re-entry	8.0×10^{-12}	1/120000000000

Outlook

- A strict implementation of the 10^{-4} casualty risk threshold implies a nearly zero casualty expectancy (subject to methodlogy).
    - In view of the Liability Convention and public opinion, this is what has to be achieved.
    - Active Debris Removal can help mitigate risk currently present in orbit, as the overall human population is expected to grow.
    - D4D is essentially required as a fall-back solution for failed controlled re-entries.
- The assessment of the risk for individual objects is essentially probabilistic in nature.
    - Methodology/models to be further analysed and developed.
    - Update of the software/standards/guidelines is needed to reflect this.