Safety Boxes Sizing for Controlled Re-entry

Application to ATV

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- ✓ **Context**
- ✓ Simulations
- ✓ Statistics
- ✓ Conclusions

Context

- ✓ Automated Transfer Vehicle
  - ❑ Mission: logistic servicing of the ISS
  - ❑ 20 tons (injection), 12 tons (nominal end of mission)
  - ❑ Re-entry analysis: many surviving fragments

⇨ Controlled re-entry

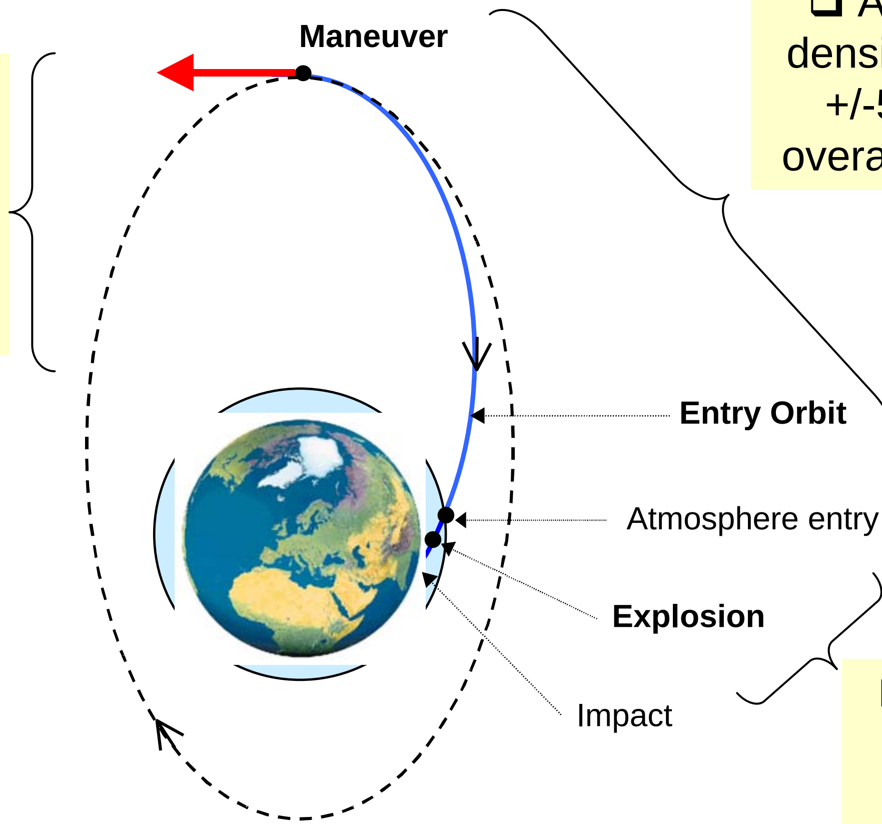
- ✓ At system level: Global risk analysis
- ✓ At ATV-CC level: Safety boxes computation for trajectory design and operations
  - ❑ Containment contour on the ground such that the probability to have a fragment falling outside corresponds to a given level (P)
    - o Declared Re-entry Area : $P = 10^{-2}$ ⇨ NOTAM
    - o Security Re-entry Area : $P = 10^{-5}$ ⇨ Trajectory design

- ✓ *Context*
- ✓ ***Simulations***
- ✓ *Statistics*
- ✓ *Conclusions*

Simulations (1/4)

Main Dispersions sources that influence ATV controlled re-entry

- ❑ Delta V: Gaussian
- ❑ Thrust level: Uniform
- ❑ Thrust orientation: Gaussian
- ❑ Mass: Gaussian, 3σ = 320 kg



- ❑ Atmospheric density: Uniform +/-50% for the overall trajectory

- ❑ Break-up / Explosion modeling

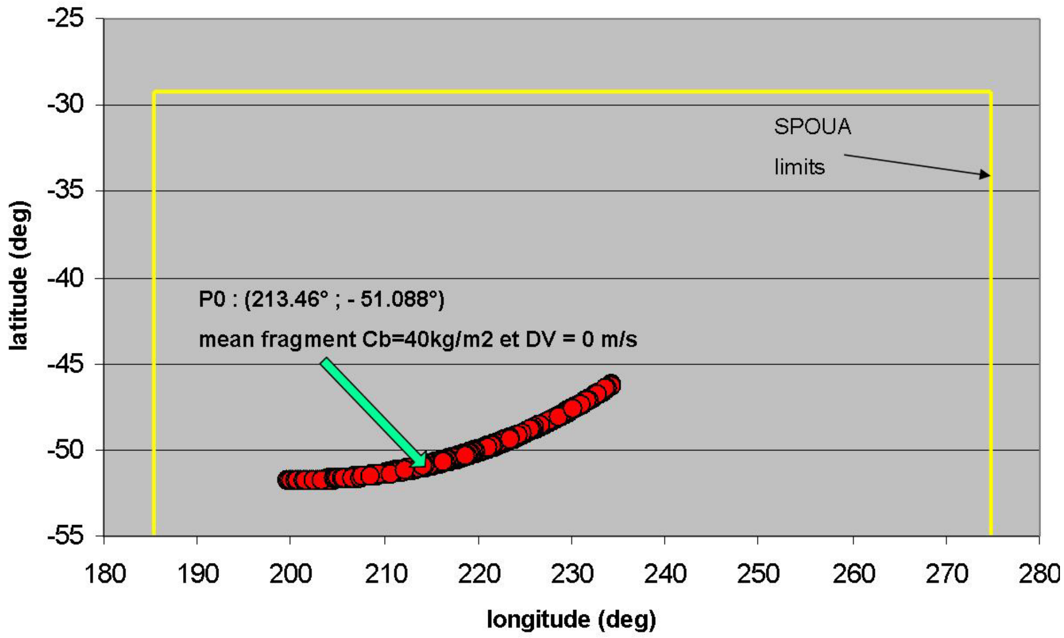
Simulations (2/4)

- ✓ Severe heating environment
  - ❑ Break-up or Explosion produces fragments
  - ❑ Fragment main characteristics: initial state vector, Cb, material
  - ❑ Survivability
- ✓ For safety boxes, a single fragmentation step occurs
  - ❑ A sample of fragments covering a very large range of Cb
  - ❑ Module of ejection velocities depends on the propellant filling
- ✓ Dispersions
  - ❑ Altitude of explosion: Gaussian 75 km, $\sigma = 2$ km
  - ❑ Fragments ballistic coefficient: Uniform
  - ❑ Fragments ejection velocity direction: Uniform

Simulations (3/4)

Dispersions sources are simulated together to assess the overall effect ⟹ Monte-Carlo method (5000 simulations)

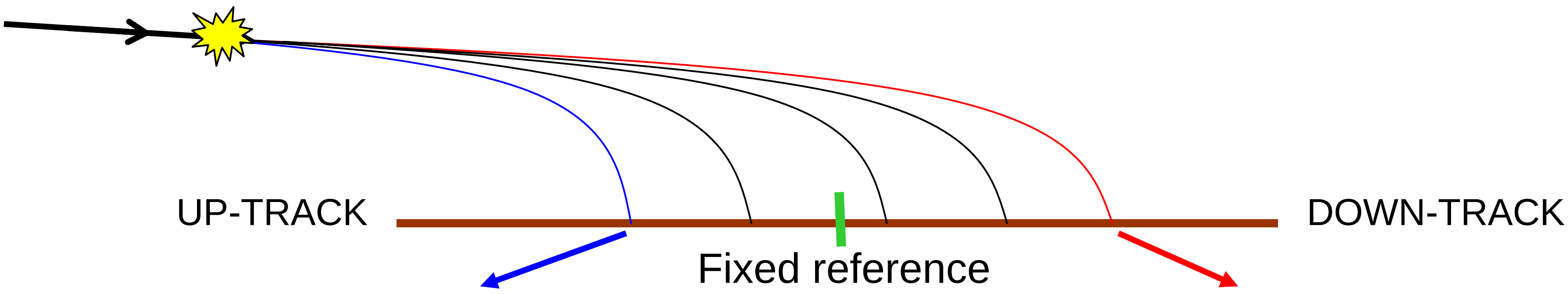
✓ Footprint analysis



✓ The problem can be restrain in one dimension

Simulations (4/4)

✓ **Typical explosion**



« Short » impact point

« Long » impact point

Monte Carlo = 5000 explosions

5000 « Short » impact points

5000 « Long » impact points

✓ **Probabilities must be derived**

- ❑ from “Short” point distribution for up-track boundary
- ❑ from “Long” point distribution for down-track boundary

- ✓ *Context*
- ✓ *Simulations*
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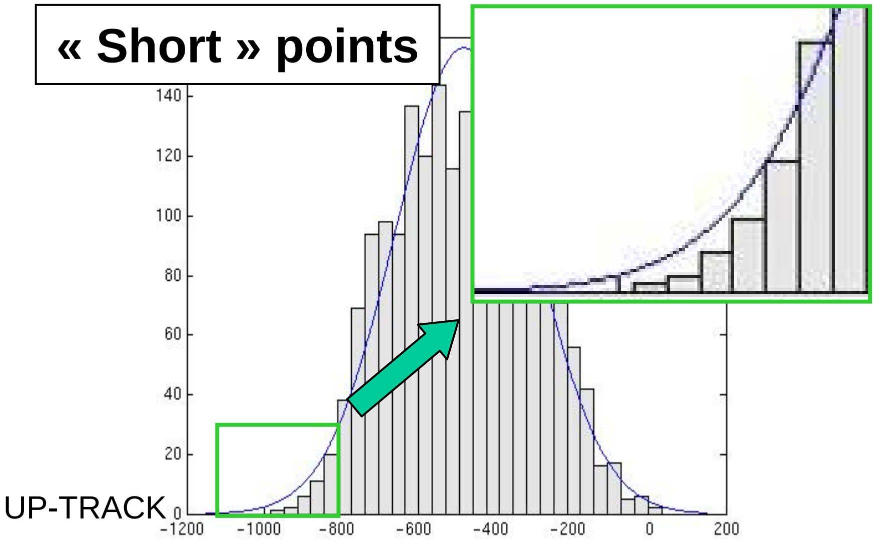
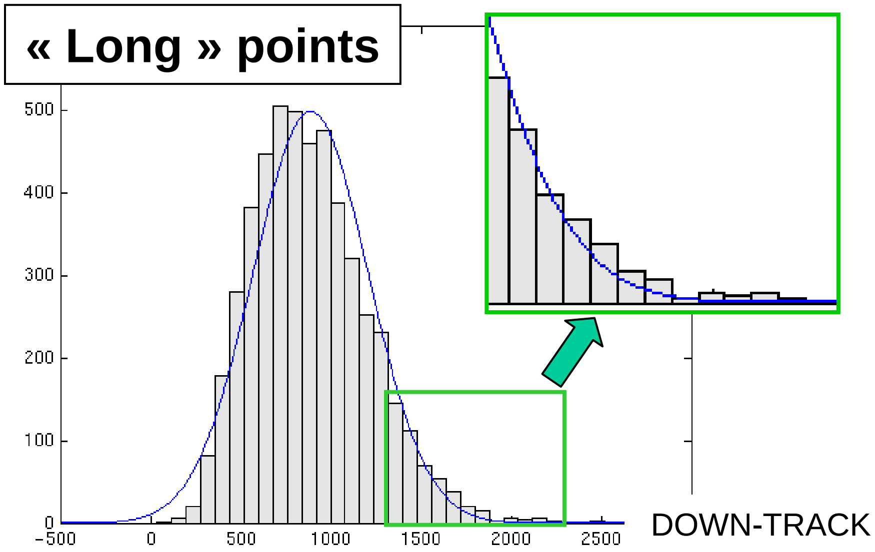
Statistics (1/4)

Gaussian approach



Over-evaluation



Under-evaluation

- ❑ Does not match the histogram for low probability density regions
- ❑ Numerical comparison between Gaussian law and the empirical cumulative density of probability shows important deviations

✓ Gaussian method is not appropriate for computing safety boxes

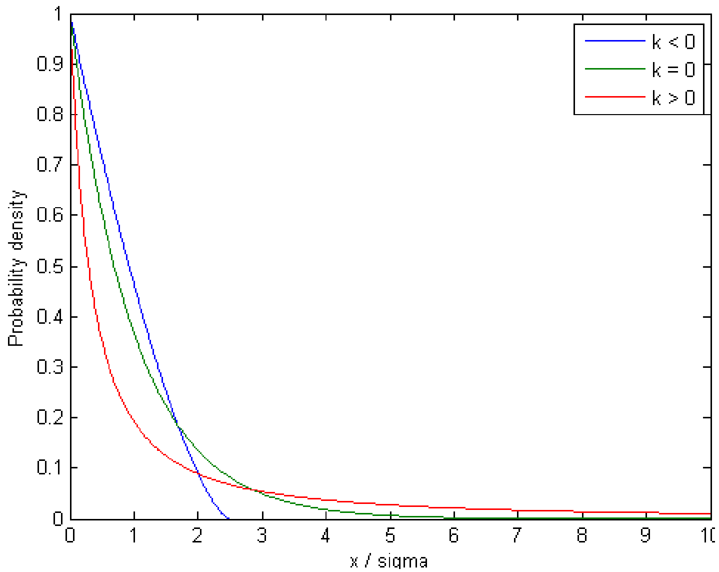
Statistics (2/4)

Extreme values prediction

- ✓ There are specific techniques to deal with tails of distribution
  - ❑ Extreme floods prediction, …
- ✓ Generalized Pareto Distribution
  - ❑ A family of distribution
  - ❑ Models a wide variety of tail of distribution

$$f(x) = \begin{cases} \frac{1}{\sigma} \cdot \left(1 + k \cdot \frac{(x-\mu)}{\sigma}\right)^{-1-1/k} & k \neq 0 \\ \frac{1}{\sigma} \cdot \exp\left(-\frac{(x-\mu)}{\sigma}\right) & k = 0 \end{cases}$$

- k = shape
- σ = scale
- μ = translation



Statistics (3/4)

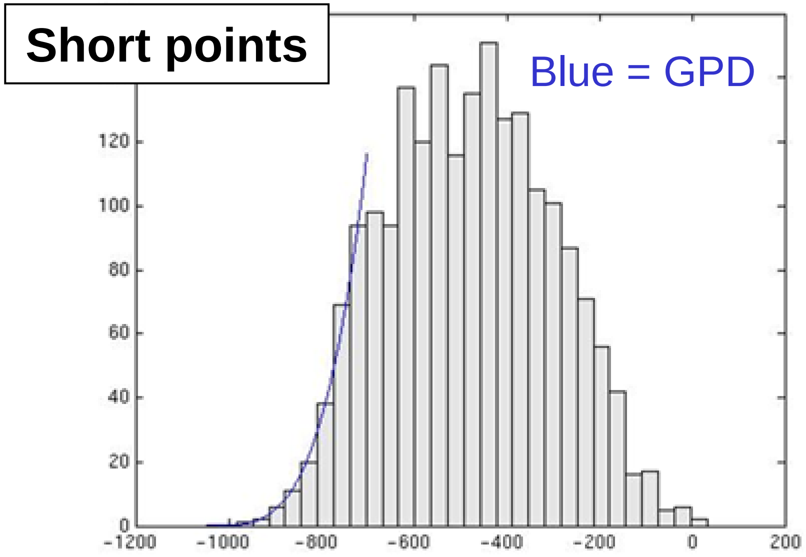
Extreme values prediction

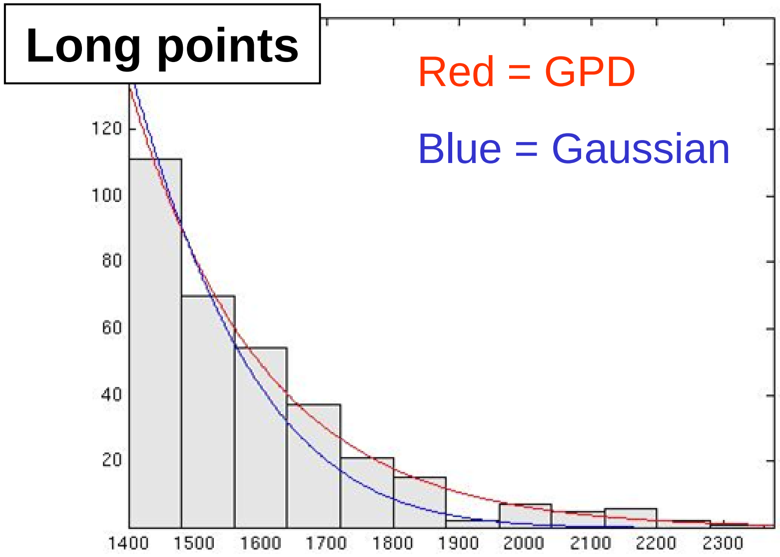
- ✓ Peaks Over Threshold method
  - ❑ Based on theoretical arguments
  - ❑ Consists in:
    - o Defining a threshold value,
    - o Discarding all data that are below the threshold
    - o Fitting a GPD on the remaining data (known as exceedences)

- ✓ The choice of the threshold is critical

- ✓ It permits “the data to decide” which distribution is appropriate

Extreme values prediction





- ❑ Matches the histogram better than the Gaussian law
- ❑ Numerical comparison between GPD and the empirical cumulative density of probability gives good results

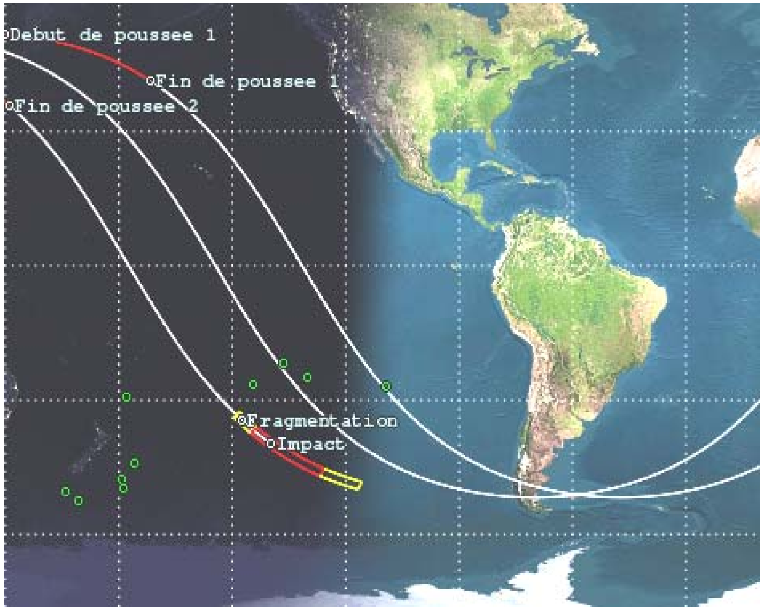
✓ This method is adequate for computing safety boxes

- ✓ *Context*
- ✓ *Simulations*
- ✓ *Statistics*
- ✓ ***Conclusions***

Conclusions (1/3)

Safety boxes for ATV Jules Verne re-entry

- ✓ Cross track boundaries for DRA and SRA
  - ❑ +/- 100km from the ground track
- ✓ Along track boundaries
  - ❑ Evaluated via GPD + POT method
  - ❑ DRA length 2415 km
  - ❑ SRA length 3050 km



- ✓ Majoring approaches in modeling have increased the safety

Conclusions (2/3)

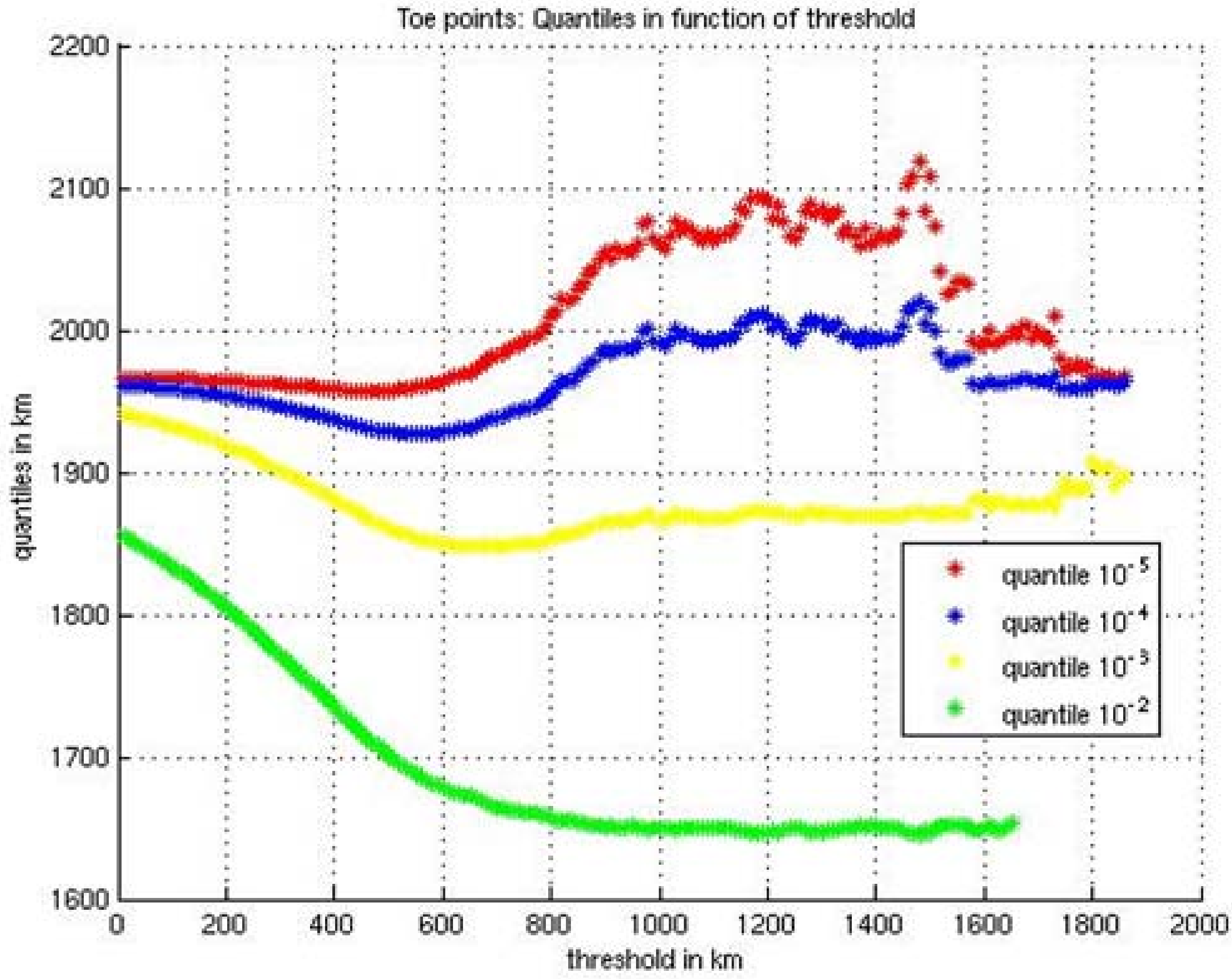
- ✓ Dedicated methods exist to deal with small probabilities
- ✓ Those methods are currently used in many safety fields
- ✓ and can also be used for space safety

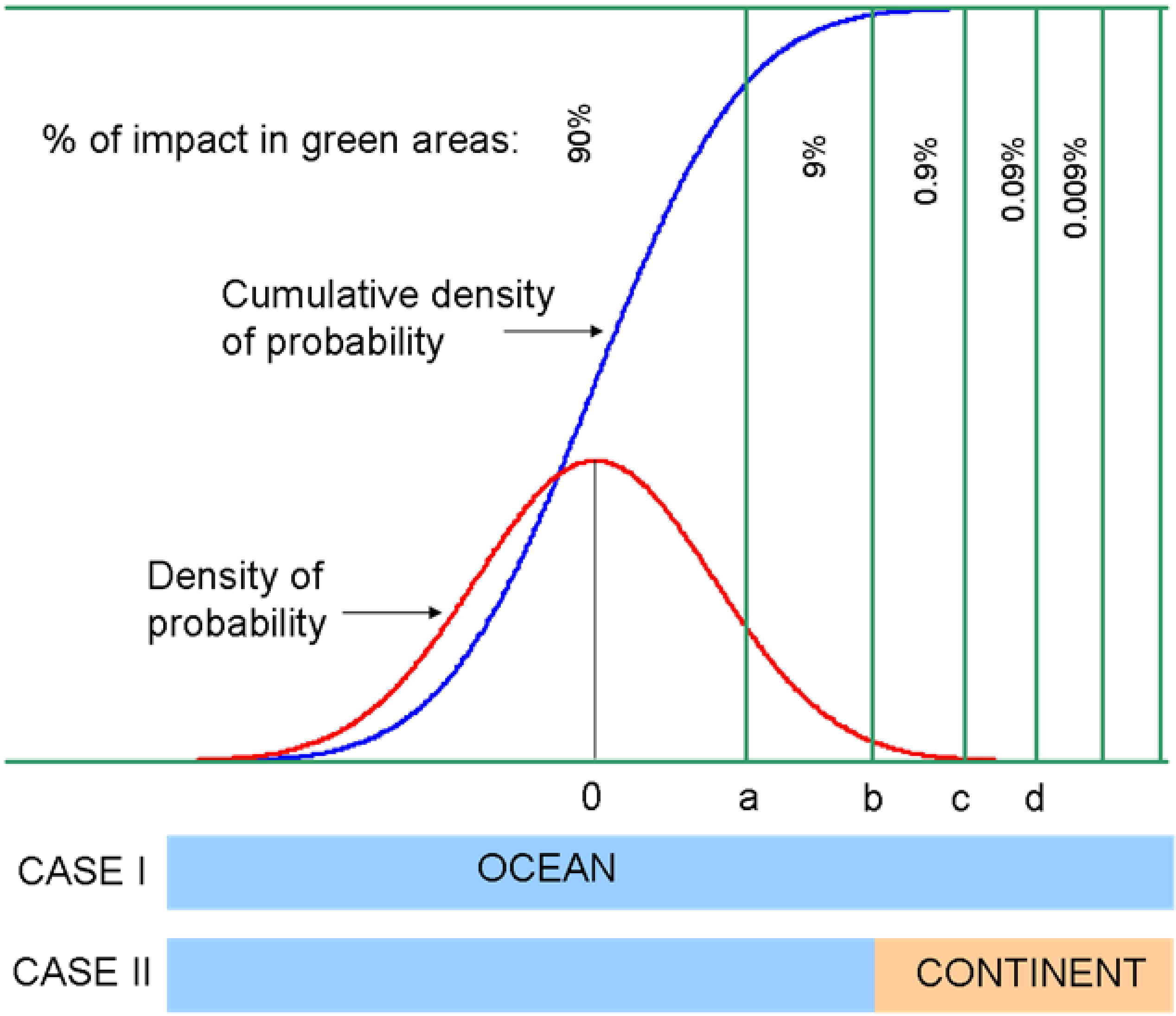
THALES

Conclusions (3/3)

- ✓ Axis of improvement for controlled re-entry safety
  - ❑ Modeling of surviving fragments
  - ❑ Occurrence of an explosion, altitude of explosion
  - ❑ Ejection velocities
- ✓ For this purpose, ATV re-entry was observed by two specially equipped planes

✓ ***Questions***


Toe points: Quantiles in function of threshold
quantiles in km
threshold in km
2200
2100
2000
1900
1800
1700
1600
0
200
400
600
800
1000
1200
1400
1600
1800
2000
quantile 10^-5
quantile 10^-4
quantile 10^-3
quantile 10^-2


% of impact in green areas:
90%
9%
0.9%
0.09%
0.009%
Cumulative density
of probability
Density of
probability
0
a
b
c
d
CASE I
OCEAN
CASE II
CONTINENT