Re-entry Predictions for Uncontrolled Satellites: Results and Challenges

Carmen Pardini and Luciano Anselmo

Space Flight Dynamics Laboratory
ISTI/CNR, Pisa, ITALY

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OUTLINE

• RE-ENTRY STATISTICS
• UNCONTROLLED RE-ENTRIES
• RE-ENTRY RISK EVALUATION
• PREDICTION UNCERTAINTIES
• CIVIL PROTECTION SUPPORT
• CONCLUSIONS
RE-ENTRY STATISTICS

As of 3 April 2013, and since the decay of the Sputnik 1 launch vehicle core stage on 1 December 1957, 22,142 cataloged orbiting objects have re-entered the Earth’s atmosphere.

<table>
<thead>
<tr>
<th>Objects</th>
<th>Number</th>
<th>Average RCS (m²)</th>
<th>RCS Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft</td>
<td>2950 (13.3%)</td>
<td>25.76</td>
<td>46.7%</td>
</tr>
<tr>
<td>Spacecraft (unmanned programs)</td>
<td>2462 (11.1%)</td>
<td>16.79</td>
<td>44.5%</td>
</tr>
<tr>
<td>Rocket bodies</td>
<td>3619 (16.3%)</td>
<td>14.17</td>
<td>53.9%</td>
</tr>
<tr>
<td>Platforms</td>
<td>543 (2.5%)</td>
<td>9.33</td>
<td>42.5%</td>
</tr>
<tr>
<td>Intact objects</td>
<td>7112 (32.1%)</td>
<td>18.35</td>
<td>50.1%</td>
</tr>
<tr>
<td>Intact objects (no manned spacecraft)</td>
<td>6624 (29.9%)</td>
<td>14.71</td>
<td>49.5%</td>
</tr>
<tr>
<td>Debris</td>
<td>15,030 (67.9%)</td>
<td>0.26</td>
<td>65.9%</td>
</tr>
<tr>
<td>Cataloged objects</td>
<td>22,142 (100%)</td>
<td>5.31</td>
<td>61.2%</td>
</tr>
</tbody>
</table>

**Intact objects**

- Accounted for 99% of the mass, i.e. ~29,000 metric tons
- Represented 32.1% of the re-entries, reduced to 29.9% by excluding the spacecraft either manned or supporting the human spaceflight programs
Re-entered Spacecraft

The re-entry of the spacecraft associated with human spaceflight accounted for:

- 16.5% of the re-entered spacecraft
- 7.4% of the re-entered spacecraft and rocket bodies
- 6.9% of the re-entered intact objects

Of the 2950 re-entered spacecraft:

- about 65% belonged to the former Soviet Union, Russia and Ukraine
- more than 29% to the United States
- less than 2% to China
- approximately 1% to Japan
Re-entered Orbital Stages

Of the 3619 re-entered upper stages
- about 76% belonged to Russia and Ukraine
- 17% to the United States
- less than 3% to China
- less than 2% to Europe and Japan

Re-entered orbital stages per country

<table>
<thead>
<tr>
<th>Country</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIS</td>
<td>2749</td>
</tr>
<tr>
<td>US</td>
<td>614</td>
</tr>
<tr>
<td>JPN</td>
<td>59</td>
</tr>
<tr>
<td>EUR</td>
<td>66</td>
</tr>
<tr>
<td>PRC</td>
<td>101</td>
</tr>
<tr>
<td>Others</td>
<td>30</td>
</tr>
</tbody>
</table>

Re-entered orbital stages per rocket family

- **DELTA**
  - US: 283 (46%)
  - CIS: 571 (21%)
  - Others: 49 (8%)
- **PEGASUS**
  - US: 116 (19%)
  - CIS: 134 (5%)
- **SATURN**
  - US: 80 (13%)
- **SCOUT**
  - US: 44 (7%)
- **THOR**
  - US: 17 (3%)
- **TITAN**
  - US: 80 (13%)
- **ATLAS**
  - US: 116 (19%)
  - CIS: 1080 (39%)
- **SL**
  - US: 9 (SL-16, 8 SL-14, 5 SL-26, 3 SL-18, others 50 (2%)
  - CIS: 1080 (39%)
  - Others 50 (2%)

...others 50 (2%)
Re-entered Debris

Re-entered debris per country

<table>
<thead>
<tr>
<th>Country</th>
<th>Percentage</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>CIS</td>
<td>61%</td>
<td>9134</td>
</tr>
<tr>
<td>US</td>
<td>27%</td>
<td>4030</td>
</tr>
<tr>
<td>PRC</td>
<td>&lt;5%</td>
<td>695</td>
</tr>
<tr>
<td>EUR</td>
<td>4%</td>
<td>633</td>
</tr>
<tr>
<td>IND</td>
<td>2%</td>
<td>276</td>
</tr>
<tr>
<td>JPN</td>
<td>&lt;1%</td>
<td>146</td>
</tr>
<tr>
<td>ISS</td>
<td>2%</td>
<td>80</td>
</tr>
<tr>
<td>Others</td>
<td></td>
<td>36</td>
</tr>
</tbody>
</table>

DELTA R/B 892 - 22%
IRIDIUM 131 - 3%
USA 194 - 5%
PEGASUS 671 - 17%
SALWIND 284 - 7%
SCOUT R/B 99 - 2%
DMSP 70 - 2%

SALWIND 284 - 7%
The debris re-entry rate was subjected to wild variations, mostly as a result of specific fragmentation events. A further (minor) modulation was introduced by the thermospheric density variations induced by the 11-year solar activity cycle.

The decay rate of intact objects was mainly driven by the launch activity, with a lesser contribution from the solar cycle and the corresponding change in the magnitude of the drag perturbation.
Correlation of the yearly decay rate of intact objects with the launch activity.
### Yearly Decay Rate averaged over the last 55, 50, 40, 30, 20, 10 and 5 years

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<thead>
<tr>
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<tbody>
<tr>
<td>Spacecraft</td>
<td>52.59</td>
<td>56.98</td>
<td>52.68</td>
<td>44.80</td>
</tr>
<tr>
<td>Spacecraft (unmanned programs)</td>
<td>43.91</td>
<td>47.56</td>
<td>41.93</td>
<td>32.80</td>
</tr>
<tr>
<td>Rocket bodies</td>
<td>64.48</td>
<td>71.48</td>
<td>75.08</td>
<td>68.50</td>
</tr>
<tr>
<td>Platforms</td>
<td>9.70</td>
<td>10.86</td>
<td>11.60</td>
<td>10.60</td>
</tr>
<tr>
<td>Intact objects</td>
<td>126.77</td>
<td>139.32</td>
<td>139.36</td>
<td>123.90</td>
</tr>
<tr>
<td>Intact objects (no manned spacecraft)</td>
<td>118.09</td>
<td>129.90</td>
<td>128.61</td>
<td>111.90</td>
</tr>
<tr>
<td>Debris</td>
<td>267.07</td>
<td>297.16</td>
<td>328.00</td>
<td>314.90</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
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<tbody>
<tr>
<td>Spacecraft</td>
<td>32.80</td>
<td>25.90</td>
<td>29.60</td>
</tr>
<tr>
<td>Spacecraft (unmanned programs)</td>
<td>21.10</td>
<td>15.30</td>
<td>16.40</td>
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<tr>
<td>Rocket bodies</td>
<td>54.10</td>
<td>41.40</td>
<td>39.00</td>
</tr>
<tr>
<td>Platforms</td>
<td>6.50</td>
<td>2.80</td>
<td>2.00</td>
</tr>
<tr>
<td>Intact objects</td>
<td>93.40</td>
<td>70.10</td>
<td>70.60</td>
</tr>
<tr>
<td>Intact objects (no manned spacecraft)</td>
<td>81.70</td>
<td>59.50</td>
<td>57.40</td>
</tr>
<tr>
<td>Debris</td>
<td>254.30</td>
<td>285.50</td>
<td>402.60</td>
</tr>
</tbody>
</table>
AVERAGE DECAY RATE OF INTACT OBJECTS, EXCLUDING THE SPACECRAFT ASSOCIATED WITH HUMAN SPACEFLIGHT PROGRAMS

Yearly Rate

<table>
<thead>
<tr>
<th>Period</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 yrs (1957-2012)</td>
<td>2.26</td>
</tr>
<tr>
<td>50 yrs (1963-2012)</td>
<td>2.49</td>
</tr>
<tr>
<td>40 yrs (1973-2012)</td>
<td>2.46</td>
</tr>
<tr>
<td>30 yrs (1983-2012)</td>
<td>2.14</td>
</tr>
<tr>
<td>20 yrs (1993-2012)</td>
<td>1.57</td>
</tr>
<tr>
<td>10 yrs (2003-2012)</td>
<td>1.14</td>
</tr>
<tr>
<td>5 yrs (2008-2012)</td>
<td>1.10</td>
</tr>
</tbody>
</table>

Weekly & Daily Rate

<table>
<thead>
<tr>
<th>Period</th>
<th>Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>55 yrs</td>
<td>0.323</td>
</tr>
<tr>
<td>50 yrs</td>
<td>0.356</td>
</tr>
<tr>
<td>40 yrs</td>
<td>0.352</td>
</tr>
<tr>
<td>30 yrs</td>
<td>0.306</td>
</tr>
<tr>
<td>20 yrs</td>
<td>0.224</td>
</tr>
<tr>
<td>10 yrs</td>
<td>0.163</td>
</tr>
<tr>
<td>5 yrs</td>
<td>0.157</td>
</tr>
</tbody>
</table>
De-orbited manned spaceships and capsules, man-tended modules, space stations, cargo vehicles and civilian spacecraft, classified spacecraft and modules which accomplished controlled re-entries (identified on the basis of information available in the open literature) were removed from the list of re-entered intact objects.

The result was that about 46% of spacecraft re-entries were controlled in some way, leaving only a 54% completely uncontrolled.

Adding the small number of controlled re-entries carried out so far by orbital upper stages [for instance, 3 in 2010, 8 in 2011 and 11 in 2012], the fraction of controlled re-entries was

- ~ 6.3% among all the decayed cataloged objects
- 19.5% among the intact objects
- 21.1% among spacecraft and rocket bodies
UNCONTROLLED RE-ENTRIES

- On average, during the Space Age, one out of five re-entries of intact objects was controlled.

- **The total mass of the uncontrolled re-entered objects was assessed to be ~11,000 metric tons**, mainly concentrated (> 98%) in almost 5700 intact objects, including nearly 5200 spacecraft (30.7%) and rocket bodies (69.3%).

- Excluding the Space Shuttle orbiters, **during the last 15 years** (1998-2012) the average re-entry mass flow of controlled and uncontrolled intact objects was around 180 metric tons per year, with a mean mass per object of approximately 2100 kg.

- **During the last 3 years** (2010-2012), nearly 50% of the re-entering mass (around 590 metric tons in total, excluding again the Space Shuttle orbiters) was controlled, accounting for about 30% of intact object re-entries (Space Shuttles included).

- Uncontrolled re-entering intact objects mainly consisted of rocket bodies (52%) and spacecraft (46%) and their average mass was around 1850 kg.
Even in the case of objects not specifically designed to survive the re-entry mechanical and thermal loads, a mass fraction between 5% and 40% of sufficiently massive bodies is able to reach the Earth’s surface.

- By applying an average surviving fraction of 15-20% to the total amount of uncontrolled re-entered mass (~11,000 metric tons), around 1650-2200 metric tons of manmade orbital debris should have survived re-entry and hit the Earth’s surface without control so far, with no confirmed case of personal injury.

- In terms of mass, number and component survivability, the uncontrolled re-entries of spent upper stages generally present a higher risk on the ground compared to spacecraft.

- Except for very specific accidental cases, as the tragic loss of the Columbia Space Shuttle orbiter (2003), or the demise of Skylab (1979), the bulk of the re-entry fragments recovered so far on the ground comes from rocket bodies.

Due to an expanding use of space and to a consequent rise in the amount of space hardware, the number of uncontrolled re-entries will remain significant in the foreseeable future.

Taking into account the concurrent increase of the world population, the ground casualty risk, even if still small compared to other commonly accepted risks linked to the lifestyle or the workplace and household safety, will presumably show a tendency to grow in the coming years.
RE-ENTRY RISK EVALUATION

- Specific guidelines to minimize the risk to human life and property on the ground have been defined. Re-entries compliant with the NASA standard 8719.14 must have a human casualty expectancy (i.e. the chance that anybody anywhere in the world will be injured by a piece of falling debris) lower than 1:10,000.

- Such alert threshold is now adopted by several organizations and countries around the world, even though only for a relatively small number of spacecraft and upper stages detailed breakup studies have been carried out, or disclosed to the public, in order to estimate their casualty expectancy.

- Therefore, every week or two, on the average, an uncontrolled re-entry violating the above mentioned alert threshold probably occurs, unknown to most of the governments and safety authorities around the world.

The overall casualty expectancy is generally estimated as:

\[
E_c \cong \frac{NA_c}{4\pi R^2 \sin L_{\text{max}}}
\]

The formula adopted by NASA for the effective casualty area due to a satellite re-entry is:

\[
A_c = \sum_{i=1}^{n} (\sqrt{A_h} + \sqrt{A_i})^2
\]

\(A_h = 0.36 \text{ m}^2\) is the projected cross sectional area of a standing human and \(A_i\) is the cross section of each individual fragment reaching the ground.

The casualty expectancy for people in the open might be slightly refined taking into account all the uncertainties underlying the computation of the effective casualty area.
RE-ENTRY RISK EVALUATION

The human casualty risk associated with an uncontrolled re-entry can be subdivided in primary and secondary:

- The **primary risk** derives from the possibility of a direct hit of people in the open by a falling fragment. It can be evaluated using Eqs. 1 and 2, taking into account that the debris kinetic energy threshold for any injury to the human body is 15 J, while a probability of fatality of 50% corresponds to a kinetic energy of 103 J.

- The **secondary risk** is associated with a potential debris impact on a building, a shelter, a high risk industrial plant (e.g. chemical or nuclear) or a vehicle (e.g. aircraft, ship, or train), possibly leading to indirect human casualties. Unfortunately there is no easy way to compute the secondary risk globally.

Concerning the sheltering of people or the protection of high risk industrial plants, attention should be paid to the fragment’s capacity to penetrate and seriously damage the structure, to the excess kinetic energy retained by the impactor if penetration occurs, and to the falling structural debris produced by the impact. The same applies, basically, to oceanic ships and low velocity trains, while high velocity trains could also incur in the secondary consequences of a high velocity impact and/or derailment.
RE-ENTRY RISK EVALUATION

For airplanes in flight even the impact with a debris practically at rest in the air could have severe consequences on board. In this case, the re-entering fragments mass and composition are more important, to assess the risk, than their kinetic energy in a reference frame at rest with respect to the ground.

- To estimate the total casualty expectancy for the commercial aircraft of registered carriers worldwide, let consider a surviving upper stage spherical tank, with a diameter of 1 m, re-entering the atmosphere from a sun-synchronous orbit.
- For people in the open $NA_c \approx 1.54 \times 10^{10}$ m$^2$ (the number of Earth inhabitants is $N \approx 7 \times 10^9$).
- Replacing the projected cross sectional area of a standing human $A_h$ with the estimated dorsal cross section of a typical airliner $A_a$ – for instance an Airbus A320 ($A_a \approx 670$ m$^2$) – and assuming that the average number of registered aircraft in the air over the world at any given time is $N_a \approx 15,000$, then $N_cA_a \approx 1.08 \times 10^7$ m$^2$.
- $NA_c/N_aA_a \approx 1426$, thus the probability of having a flying aircraft hit by the re-entering rocket body tank is three orders of magnitude less than the probability to strike somebody anywhere in the world.
- Even considering an average of about 150 passengers per airplane and an absolutely catastrophic outcome for the potential impact, the effective passenger casualty expectancy would remain one order of magnitude less than the standard casualty expectancy computed for people in the open.

Therefore, Eqs. 1 and 2 applied in the standard way to people in the open still provide the correct order of magnitude of the casualty expectancy for uncontrolled re-entry events, including much more complicated situations, as flying aircraft.
PREDICTION UNCERTAINTIES

After 55 years of space activity, predicting the re-entry time and location of an uncontrolled satellite remains a very tricky task

- The satellite can re-enter anywhere on a large portion of the Earth surface, putting all the locations within the latitude band defined by the orbit inclination into the risk zone

There is considerable uncertainty in the estimation of the re-entry epoch due to

- sometimes sparse and inaccurate tracking data
- complicate shape and unknown attitude evolution of the re-entering object
- biases and stochastic inaccuracies affecting the computation of the atmospheric density at the altitudes of interest
- magnitude, variability and prediction errors of solar and geomagnetic activity
- mismodeling of gas-surface interactions and drag coefficient

All these uncertainty sources combine in a complex way, depending on the specific properties of the re-entering object considered and on the particular space environment conditions experienced during the final phase of the orbital decay

Therefore, even applying the same (best) models, methods and procedures, the overall relative re-entry prediction errors may be quite different for various objects and in diverse epochs
The re-entry prediction campaigns

- Involved 10 spacecraft (1, 2, 5, 6, 7, 8, 11, 13, 14, 15), 4 rocket bodies (3, 4, 9, 12) and 1 large mission related object (10)
- Were carried out during the last 15 years (1998-2012), covering periods of high (2, 3, 4), moderate (1, 5, 13, 14, 15) and low (6, 7, 8, 9, 10, 11, 12) solar activity
- All the inclinations were > 50°
- 14 out of 15 objects were in nearly circular low decaying orbits
- The only exception was represented by object 11, in highly elliptical Molniya orbit, whose re-entry was mainly the result of the perigee lowering induced by luni-solar gravitational perturbations, and not by atmospheric drag

The average campaign duration was about 10 days, so the total campaign averages refer to all the re-entry predictions computed during the last 10 days of the uncontrolled satellite lifetime

The mean relative prediction errors obtained during the last 48 hours are presented as well
PREDICTION UNCERTAINTIES

The overall mean prediction error was

- < 10% of the residual lifetime in 11 out of 15 campaigns
- < 5% in 5 cases
- < 20% in all 15 cases

During the last 48 hours, the mean prediction error was

- < 5% in 4 cases
- < 10% in 11 cases
- < 20% in 14 out of 15 campaigns

The outlier (object 2) was a small spherical spacecraft characterized by a peculiar gas-surface interaction and this, together with quite active and variable space environment conditions, probably played a role in attaining a mean relative error of 27% during the last 48 hours.

Disregarding object 2 for the reasons just mentioned, object 11 for the highly elliptical orbit not properly managed with the methods and procedures commonly adopted for the decay from nearly circular orbits, and also object 13, for the complex shape and the huge attitude changes displayed in the last 48 hours, the only clear regularity emerging is that low solar and geomagnetic activity conditions, coupled with a small variability, lead to better predictions, with average relative errors of 10% or less.
Instead, high solar activity and unsettled geomagnetic conditions, in particular if prone to wide variability, typically result in mean relative errors of 15-20%, but with possible excursions up to 30%.

This is particularly true during the last week of satellite lifetime, when an unpredicted geomagnetic storm, induced by a massive coronal mass ejection in the Sun, may produce a sensible increase of the atmospheric density at low altitude, which may persist for several hours (up to a few days), causing a sudden acceleration of the orbital decay rate and the consequent reduction of the residual lifetime. The size of the effect is a function of the geomagnetic storm severity and the satellite residual lifetime.

In conclusion, based on these results and on the experience accumulated in other tens of re-entry predictions and decay analyses:

- A relative prediction error of at least ±20% should be adopted to compute the uncertainty windows associated with uncontrolled satellite re-entry predictions, in order to reasonably cover all the possible error sources.

- In specific cases of high solar and geomagnetic activity, solar flare and coronal mass ejection alert and/or satellites of particularly complex shape and attitude dynamics, a more conservative prediction error of ±25-30% should be considered, in particular during the last 2-3 days of residual lifetime.
PREDICTION UNCERTAINTIES

Evolution of uncertainty windows for objects 13 [UARS], 14 [ROSAT] and 15 [Phobos-Grunt]

- For UARS they were obtained by varying by ± 20% the fitted ballistic parameter used to propagate the satellite trajectory
- For ROSAT this variation range was increased to ± 25%
- For Phobos-Grunt the uncertainty windows were obtained by directly varying the nominal residual lifetime by ± 25%
CIVIL PROTECTION SUPPORT

The attention of the civil protection authorities of a country is focused, of course, on the national territory, so the relevant question for any meaningful planning is

“Given a certain uncertainty window, where and when a re-entering satellite fragment might cross the national airspace and hit the ground?”

Being affected by significant intrinsic uncertainties, the nominal re-entry time is useless for civil protection planning and applications

The definition of appropriate re-entry uncertainty windows is necessary for such applications
CIVIL PROTECTION SUPPORT

The amplitude of the uncertainty windows depends on how far away from re-entry is the epoch of the last reliable satellite state vector used for analysis and prediction. Due to the very fast satellite velocity, this translates into huge along-track uncertainties even a few hours before an uncontrolled re-entry.

Sub-satellite track for object 10 [EAS] included in an uncertainty window computed from an orbit determined around 12 hours before re-entry by varying by ±20% the drag perturbation.

Sub-satellite track for object 10 included in an uncertainty window computed from an orbit determined around 6 hours before re-entry by varying by ±20% the drag perturbation.
CIVIL PROTECTION SUPPORT

Also when the flux of orbit determinations is steady and optimal, there is an unavoidable processing and communication delay of at least 2-3 hours between the orbit determination epoch and the release of the corresponding re-entry prediction.

So the final forecasts issued during the last hour or minutes preceding the actual re-entry are based on a state vector with a 2-3 hours old epoch.

The consequence of this is that the predictions issued around 3 hours before re-entry have a typical along-track uncertainty of one orbit (i.e. ~40,000 km), while those issued immediately before re-entry maintain a typical along-track uncertainty of half an orbit (i.e. ~20,000 km).

Moreover, the use of different standard atmospheric density models may lead to along-track differences of thousands of kilometers among the nominal impact points (COIW).
CIVIL PROTECTION SUPPORT

For each sub-satellite location included in the re-entry window, debris impact is possible, but not certain; however, in each place, the eventual impact may occur only during a specific risk time window, which can be therefore used to plan risk mitigation measures on the ground and in the overhead airspace.

- In practice, starting 3-4 days before the satellite decay from orbit, the nominal predicted trajectory is slightly modified, through small changes of the ballistic parameter, in order to obtain simulated re-entries over the national territory in the time interval corresponding to the current uncertainty window.

- The re-entry ground tracks found in this way are much more stable and less affected by propagation uncertainties, being computed with the “right” times and also including the re-entry dynamics of representative fragments up to ground impact.

- Nominal impact times and ground tracks are therefore integrated with:
  - A small time dispersion of a few minutes to account for initial conditions variability.
  - A larger time dispersion (tens of minutes) to take into account the different flight times of diverse fragments with distinct ballistic properties, including small particles not representing a hazard on the ground, but possibly dangerous for aircraft crossing the airspace affected by the re-entry.
  - A cross-track safety margin to account for the expected dispersion of the fragments and the trajectory residual uncertainties.
CIVIL PROTECTION SUPPORT

For Italy, the “risk” time windows have typically an amplitude of about 30 minutes, including the airspace crossing from the altitude of 10 km to ground impact.

After the identification of the few potentially critical tracks and corresponding risk time windows, a relevant task of the re-entry prediction process is the elimination of the tracks left outside the progressively shrinking global uncertainty window, focusing the attention on what remains.

E.g. PHOBOS-GRUNT [Objects 15]

- The first “risk” tracks for Italy were issued to the national civil protection authorities about 57 hours before actual reentry.
- At that time the uncertainty window was still 28-hour wide, but the satellite re-entry tracks possibly affecting the Italian territory were already reduced to 3.
- Each had an associated “risk” time window of 30 minutes.
- A ground swath of ±120 km around the nominal track was considered.
- 10 hours before reentry, 2 “risk” tracks (1, 3) moved outside the 7-hour wide global uncertainty window.
- Track 2 remained in play until the very end, i.e. until it was confirmed that such pass over Europe had not occurred, being the probe re-entered before crossing the Atlantic Ocean.

This information (very specific geographic areas and the associated short alert time intervals) is easy to communicate and understand for people not familiar with orbital and re-entry dynamics.
CONCLUSIONS

- Currently, approximately 70% of the re-entries of intact orbital objects are uncontrolled, corresponding to about 50% of the returning mass, i.e. \(~100\) metric tons per year

- On average, there is one spacecraft or rocket body uncontrolled re-entry every week, with an average mass around 2000 kg

- Even though a detailed demise analysis is available only occasionally, in many cases the alert casualty expectancy threshold of 1:10,000 is probably violated

- Re-entry predictions are affected by various sources of inevitable uncertainty and, in spite of decades of efforts, mean relative errors of 20% often occur

- This means that even predictions issued 3 hours before re-entry may be affected by an along-track uncertainty of 40,000 km (corresponding to one orbital path), possibly halved during the last hour

- However, specific methods and procedures have been developed to provide understandable and unambiguous information useful for civil protection planning and applications