SATELLITE RE-ENTRY PREDICTION PRODUCTS FOR CIVIL PROTECTION APPLICATIONS

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Credit: NASA (UARS)

Credit: Michael-Carroll (Phobos-Grunt re-entry)

Photograph: Enver Essop/EPA

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Credit: wallpaperstock.net (aurora borealis from space)

Objectives

Present the work carried out so far for the Italian territory and air space

- **Approaches and procedures are described in detail**
- **Examples of application relative to real re-entries occurred during the last decade are given**

***In the attempt* to provide prescriptions on how our methods and strategies might be extended and applied to wider areas of the planet, possibly the entire world**

In order to supply

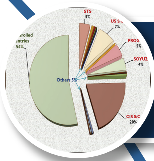
"more accurate"

early alerts to aircraft and on the ground, in terms of reasonably slim risk time windows

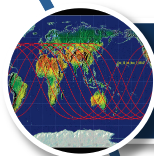
&

re-entry tracks for any location possibly affected by the re-entering debris

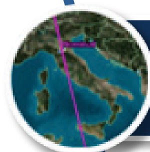
OUTLINE



- Introduction



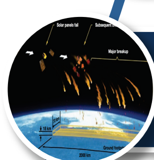
- Re-entry uncertainty windows



- Ground tracks uncertainty

- Civil protection applications

- Regional risk time windows

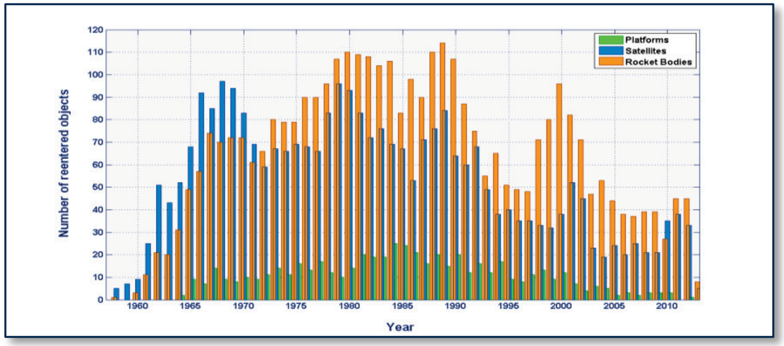


- Re-entry debris distribution

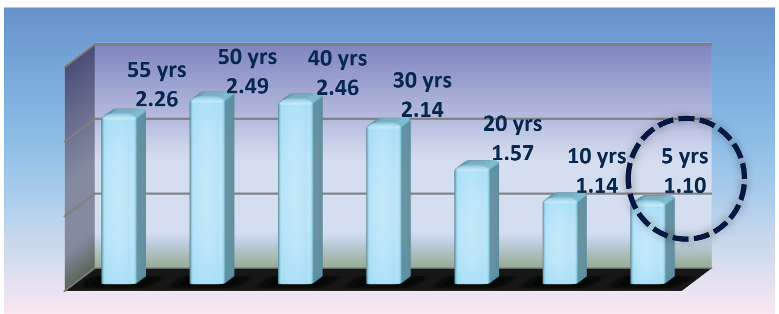
- Recent re-entry examples

Introduction

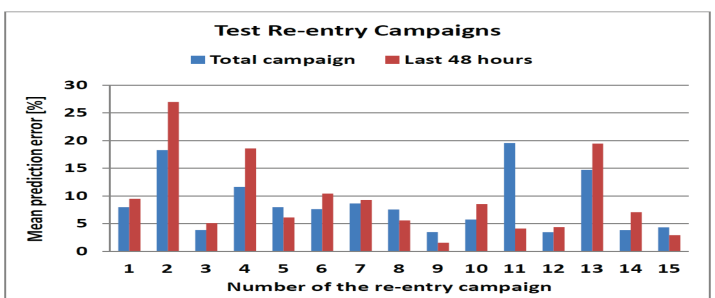
Yearly decay rate of intact objects



Average weekly decay rate of intact objects



Prediction uncertainties



- Currently, around 70% of the re-entries of intact orbital objects are uncontrolled, corresponding to ~ 50% of the returning mass, i.e. ~100 metric tons per year
- There is one spacecraft or rocket body uncontrolled re-entry every week, with an average mass around 2000 kg
- Re-entry predictions are affected by various sources of inevitable uncertainty: mean relative errors of ~ 20% should be typically expected in the estimation of the residual lifetime
- A global re-entry uncertainty window still includes many revolutions – overflying most of the planet – even a few days before orbital decay
- Predictions may be affected by an along-track uncertainty of 40,000 km – one full orbital path – just 3 hours before re-entry

Such kind of information is not much useful and manageable for civil protection applications

Hence, since 2003 specific approaches and procedures have been developed, producing output products tailored for civil protection applications by the Italian national authorities

Re-entry uncertainty windows

To reasonably cover all *possible error sources*

A relative prediction error of ±20% should be adopted to compute the uncertainty windows associated with re-entry epoch predictions

- *Sparse and inaccurate tracking data*
- *Mismodeling of gas-surface interactions and drag coefficient*
- *Magnitude, variability and prediction errors of solar and geomagnetic activity*
- *Complicate shape and unknown attitude evolution of the re-entering object*
- *Biases and stochastic inaccuracies in the estimation of the atmospheric density*

- In specific cases, more conservative prediction errors, up to ±30%, should be considered, in particular during the last 2-3 days of residual lifetime

THESE RE-ENTRY TIME UNCERTAINTIES ARE QUITE HUGE

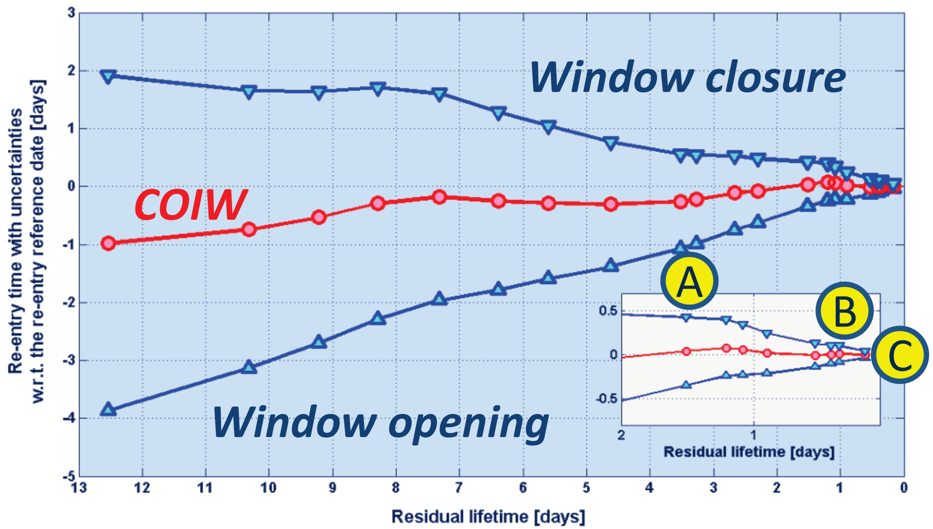
- A couple of days before re-entry, the event occurrence is generally uncertain by 20 hours, corresponding to about 13 full revolutions of the object around the Earth

- At the beginning of the last day, the uncertainty window is still 10 hours wide, including more than 6 satellite revolutions
- The very high orbital velocity at low altitudes translates into large along-track spatial uncertainties even a few hours before decay

Satellite residual lifetime since the last determined orbit	Amplitude of the uncertainty window	Orbital sub-satellite tracks included in the uncertainty window
10 days	± 2 days	≈ 64
5 days	± 1 day	≈ 32
3 days	± 14.4 hours	≈ 19
2 days	± 9.6 hours	≈ 13
1 day	± 4.8 hours	≈ 6.4
12 hours	± 2.4 hours	≈ 3.2
6 hours	± 1.2 hours	≈ 1.6
4 hours	± 0.8 hours	≈ 1.1
3 hours	± 0.6 hours	≈ 0.8
2 hours	± 0.4 hours	≈ 0.5
1 hour	± 0.2 hours	≈ 0.3

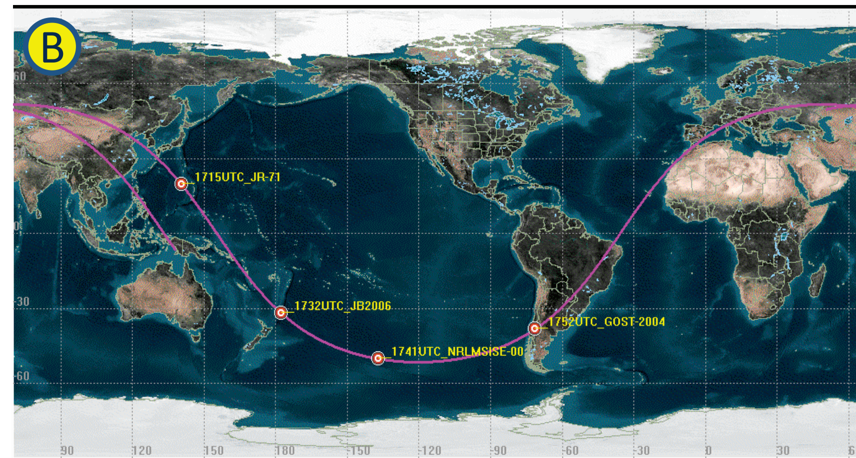
Example of re-entry uncertainty windows

***PHOBOS-GRUNT** - Re-entry window: residual lifetime ±25% - Reference re-entry time at 10 km: 15 January 2012, 17:53 UTC*



TLE: 15 January 2012 – 14:04 UTC

2012/01/15 16:55 – 2012/01/15 17:52 – 2012/01/15 18:44



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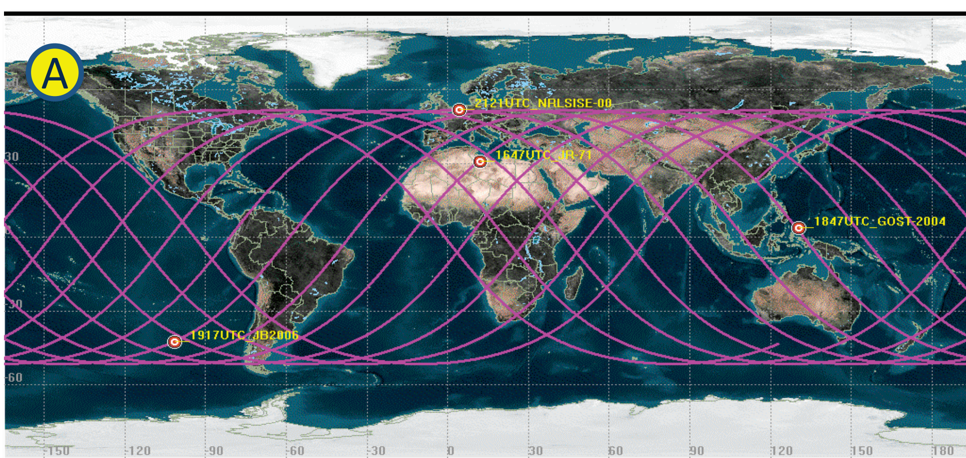

TLE: 15 January 2012 – 17:03 UTC

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Ground tracks uncertainty

- **In addition to the huge along-track uncertainty associated with the global re-entry time windows, the sub-satellite tracks may also result quite inaccurate in the cross-track direction, as a direct consequence of the trajectory propagation errors and Earth rotation**

Nodal crossing time error (minutes)	Shift of the sub-satellite ground track at the equator (km)
1	≈ 28
5	≈ 140
10	≈ 279
15	≈ 419
20	≈ 558

- ***An anticipated crossing causes an eastward drift of the ground track, while a delayed crossing causes a westward drift***

Taking into account that the Earth surface at the equator moves eastward at the velocity of 0.465 km/s

- **A difference of just 1 minute in the equator crossing would correspond to a sub-satellite track shift of ~ 28 km**
- **A difference of 15 minutes would correspond to a ground shift of ~ 419 km**

Consequences of the uncertainty in the satellite overflight times

- **Due to the fact that even 24 hours before re-entry the predicted overflight times included in the uncertainty window may be affected by errors as large as 10-15 minutes (or more)**

Predicted sub-satellite ground track over Italy of a re-entering satellite in nearly circular orbit at sun-synchronous inclination

Eastward drift of the sub-satellite ground track over Italy caused by an ascending nodal crossing anticipated by 10 minutes

Westward drift of the sub-satellite ground track over Italy caused by an ascending nodal crossing delayed by 10 minutes

- **The trajectory cross-track uncertainty cannot be ignored, *making the plots of the ground tracks issued by many during the final days of orbital lifetime not only useless for civil protection applications, but also misleading***

Civil protection applications [1]

- The re-entry prediction standard products for potentially risky and uncontrolled space objects
- Are of no or very limited use for civil protection applications

Nominal decay forecast

- Its intrinsic large uncertainty makes it absolutely useless for civil protection planning

Global uncertainty time window

- Provides relevant information, identifying the time interval in which the re-entry should be expected, somewhere in the world. But this interval remains too large until re-entry, so it is not possible to devise and apply practical precautionary civil protection measures based on it

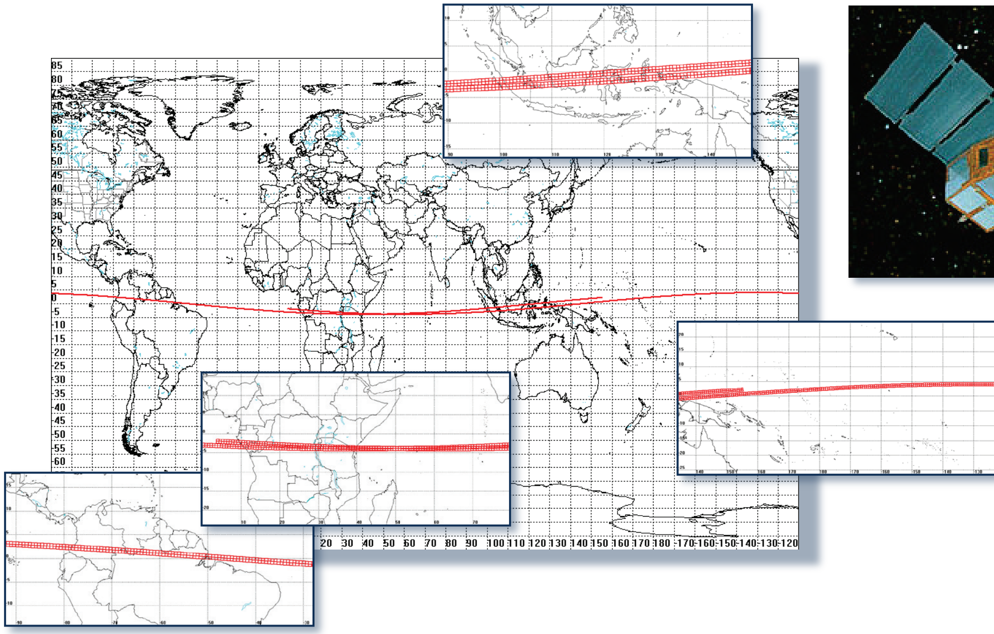
Sub-satellite ground tracks

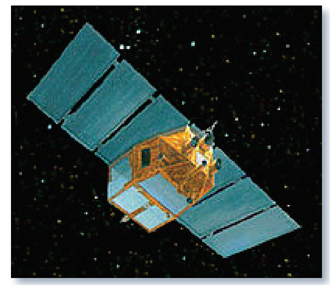
- Inside the global uncertainty window, the re-entry location remains quite undetermined, along a varying number of orbital sub-satellite tracks, themselves possibly affected by a considerable cross-track error

- **The locations possibly at risk in a given area, *for instance in Italy*, cannot be identified reasonably ahead of re-entry with this information**

Civil protection applications [2]

In order to overcome these problems, a new approach was devised and applied in Italy to real re-entry predictions campaigns since the orbital decay of the BeppoSAX spacecraft in 2003





A question is relevant for meaningful civil protection planning

«Given a certain global uncertainty time window, where and when a re-entering satellite fragment might cross the airspace and hit the ground on a specific area of the world (e.g. Italy) overflown by the falling uncontrolled object?»

- **For each overflown location included in the global uncertainty time window, the re-entry and debris ground impact is possible but not certain**

- **However, in each place the eventual re-entry or impact may occur only during a specific and quite accurate risk time window, which can be used to plan risk mitigation measures on the ground and in the overhead airspace**

Civil protection applications [3]

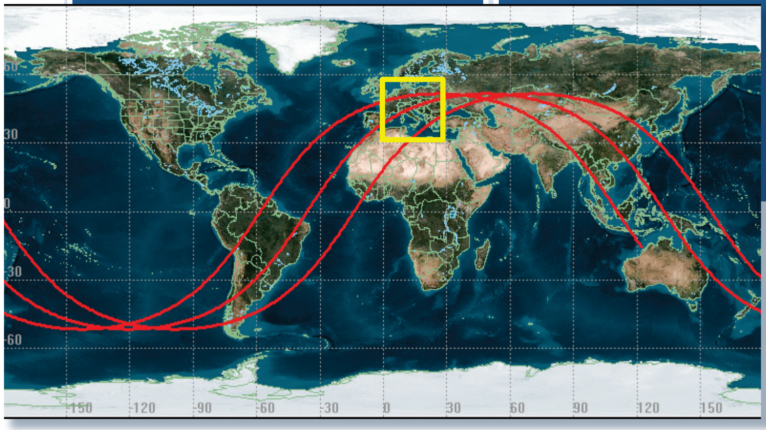
But how to compute the risk time windows for each overflown area included in the global uncertainty time window i.e. the "REGIONAL RISK TIME WINDOWS"?

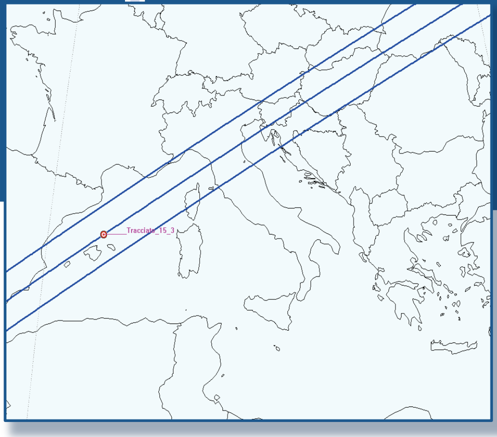
Step 1
Satellite re-entry opportunities are identified on a given area during the current global uncertainty time window

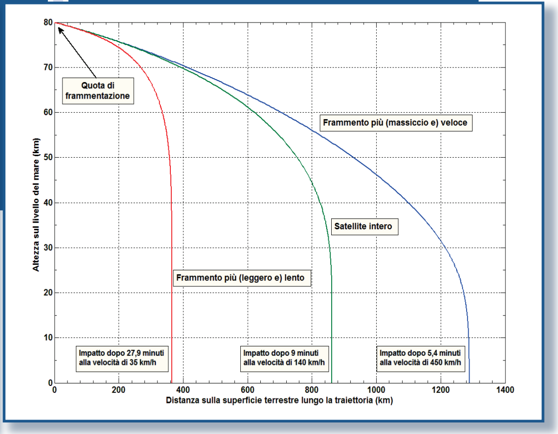
Step 2
A small time dispersion (e.g. ± 2 min) is considered to take into account the finite size of the area of interest around a re-entry opportunity (e.g. ± 900 km)

Step 3
A larger time dispersion (tens of minutes) is considered to take into account the different flight times of diverse satellite fragments with distinct ballistic parameters

Step 4
A small time dispersion (a few minutes) is considered to account for the effects of initial conditions and trajectory propagation errors







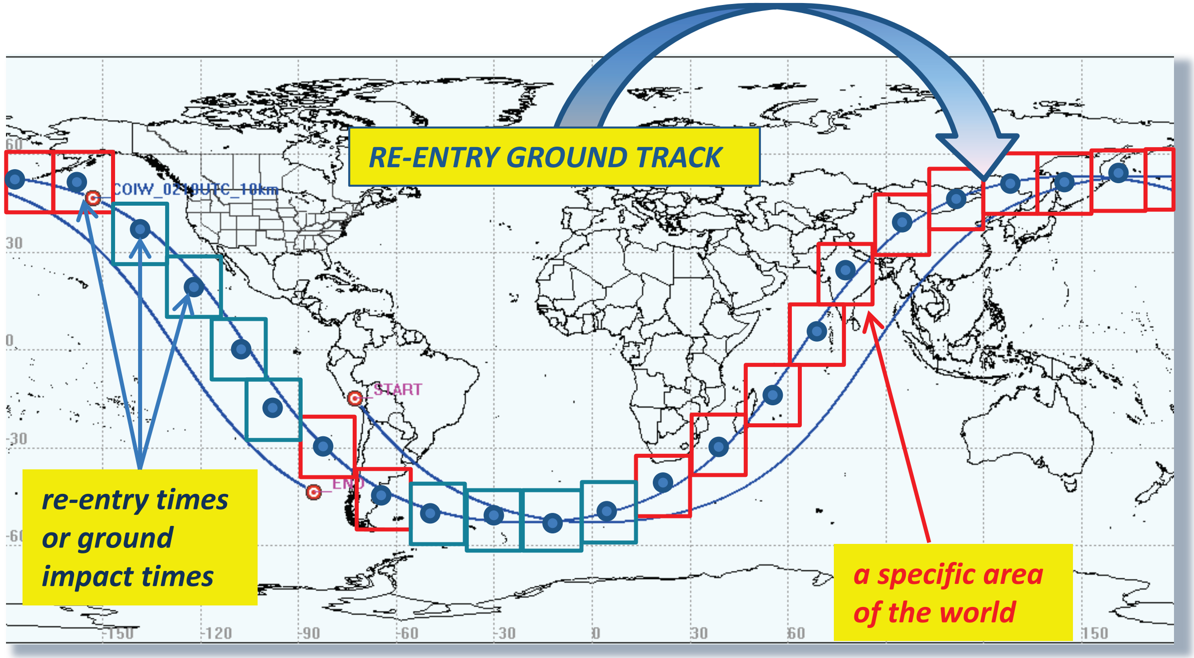
Re-entry opportunities – Step 1

Computation of the satellite re-entry or "intact" impact opportunities

- *The trajectory propagation uncertainty – leading to the wide global uncertainty time window – is dominated by the atmospheric drag mismodeling, i.e. by the inaccuracy of the product: $C_D \cdot A \cdot \rho$*
- *Possible variations of the re-entry time included in the uncertainty window are just the consequence of possible variations of this product, which may be then searched iteratively inside the expected variation range (for instance by varying C_D or A)*

- **Even 3-4 days before the satellite plunge into the atmosphere, the potential re-entry times over specific geographical locations (e.g. at a geodetic altitude in between 100 and 80 km) can be estimated quite accurately**
- **This is a direct consequence of "anchoring" the satellite dynamical evolution with the Earth rotation, in order to obtain a re-entry over a selected area of the planet**
- **Moreover, 3-4 days in advance offer a very good margin for civil protection preparations, and the further accuracy improvements possible in the following days may be used to refine and update an already clear picture of the situation and its expected evolution**
- ***The experience gained in several re-entry prediction campaigns has shown that, in alternative to the re-entry times, the simulated ground impact times of the intact decaying object can be used as well***
- **From a practical point of view, the simulated ground impact times of the "fictitious" intact satellite and the associated ground tracks over the selected area of the world are easier to use for accurately defining in advance the times and locations potentially affected by a debris fall**

Finite size of the considered area – Step 2



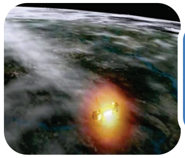
- A re-entering satellite in nearly circular orbit overflies more than 455 km in ~ 1 minute
- Moving along the correct ground track 910 km forward or backward, the computed event times – *re-entry time or ground impact time of the "intact" object* – are shifted by 2 minutes, respectively forward or backward
- If the re-entry ground tracks included in the global uncertainty time window are subdivided in arcs 1820 km long, the event time computed in the middle entails a maximum time error over the full arc of ±2 minutes

- A ±2 minutes difference in the event timing inside the chosen arc is small compared to the flight time dispersion of the breakup fragments, so it can be tolerated in order to maintain reasonably small the number of fictitious re-entries to be simulated
- For Earth surface regions sufficiently wide to include Italy and a significant portion of the surrounding lands and seas, each possible re-entry track may be accurately modeled by simulating only one re-entry, or ground impact, inside the area of interest
- Considering wider regions of the planet overflown by the satellite, the exercise must be repeated for the applicable number of arcs, about 22 per orbit if a maximum timing error of ±2 minutes is deemed acceptable

Different flight times of the satellite fragments - Step 3

A further step in the definition of a
"REGIONAL RISK TIME WINDOW"
must take into account

The different flight times of the satellite fragments



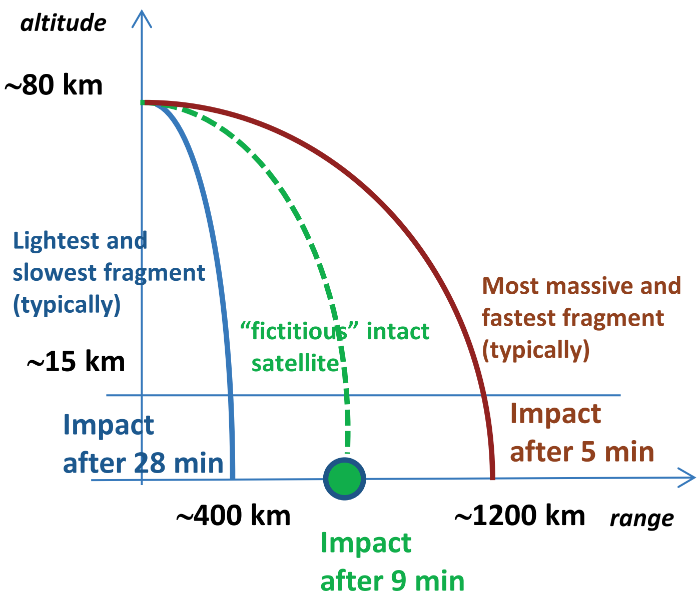
Able to survive the harsh conditions of the re-entry

Crossing the airspace below the altitude of ~15 km

Impacting the ground

- **These fragments are characterized by distinct ballistic properties, fragmentation altitudes and ablation histories, and obviously vary as a function of the nature of the parent object**
- **Their timing dispersion, in terms of airspace crossing and ground impact, is typically a few tens of minutes wide and includes the time of flight of the "fictitious" intact parent object, taken as reference to set the absolute scale of time**

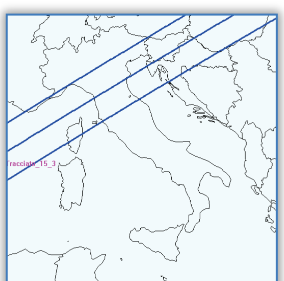
Regional risk time windows



Around any possible re-entry location included in the global uncertainty time window

- **It is possible to define a quite accurate regional risk time window accounting for**
  - **The dispersion of the fragments (a few tens of minutes)**
  - **The finite size of the considered area (±2 minutes in our example)**
  - **A further rather conservative time dispersion (a few minutes), to include the unaccounted for effects of initial conditions and trajectory propagation errors**

- **The re-entry probability on a given area will remain small until the end (*of the order of a few percent or less*), but the eventual debris fall and impact may occur only during the defined risk time window**

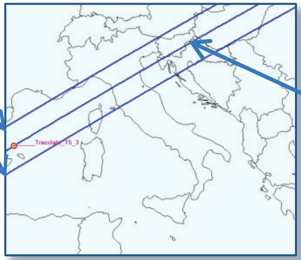


For a region sufficiently wide to include Italy, it was shown that, depending on the specific cases analyzed, risk time windows 30-40 minutes wide were appropriate and could be accurately identified already 3-4 days ahead of the foreseen re-entry, resulting extremely useful for civil protection planning and applications

Phobos-Grunt re-entry – Risk time window: 18:14–18:44 UTC on Sunday 15 January 2012

Volume of airspace and surface on the ground associated with the regional risk time window

Starting from the accurate re-entry ground track for the area of interest, it is possible to obtain the volume of airspace and the surface on the ground associated with the regional risk time window



A CROSS-TRACK SAFETY MARGIN must be defined, taking into account

- **The expected dispersion of the fragments perpendicularly to the satellite trajectory**
  - Depends on the breakup nature and debris endo-atmospheric dynamics
  - Might amount to as much as several tens of kilometers
- **The residual cross-track trajectory uncertainty due to the mismodeled part of the actual decay evolution during the last days of residual lifetime**
  - Amounts to a few tens of kilometers 3-4 days before the orbital decay
  - Progressively decreases as the re-entry epoch is approaching
- **The effects of the prevailing or predicted winds in the stratosphere and in the troposphere**
  - The cross-track drift of macroscopic fragments exposed to winds during the final phase of (nearly) vertical fall is less than a few tens of kilometers

Cross-track safety margin considering the relevant fragments in typical uncontrolled re-entries

From a safety point of view, the relevant fragments in typical uncontrolled re-entries are those with

- A ground impact energy ≥ 15 J, able to injure a human body in the open
- A terminal kinetic energy ≥ 103 J, associated with a 50% probability of human fatality
- A potential capability to lead to a catastrophic impact with a passenger aircraft in flight

Moreover

- A 1 g compact piece of steel may pose a significant hazard to certain types of aircraft
- For commercial passenger aircraft with aluminum skin, penetration in flight requires the impact with debris of more than 100 g, and fragments in excess of 300 g are probably needed to induce catastrophic consequences, irrespective of the impact location

CROSS-TRACK SAFETY MARGIN

Limiting the attention to the relevant fragments and depending on the specific nature of the re-entering parent object

- 3-4 days before orbital decay a safety margin swath of ±90-200 km around the computed re-entry trajectory may be assumed
- It may be reduced progressively to ±80-120 km during the last 24-48 hours

Availability of the information needed for an effective civil protection evaluation and planning

Availability, 3-4 days before re-entry and for a region of interest, of a ground hazard footprint with an overlying volume of airspace, associated with a reasonably compact risk time window of 30-40 minutes
Such information is sufficiently accurate, reliable, unambiguous, relatively stable and very easy to explain, understand and manage also for personnel not expert in orbital dynamics

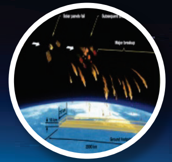
For a region embracing Italy

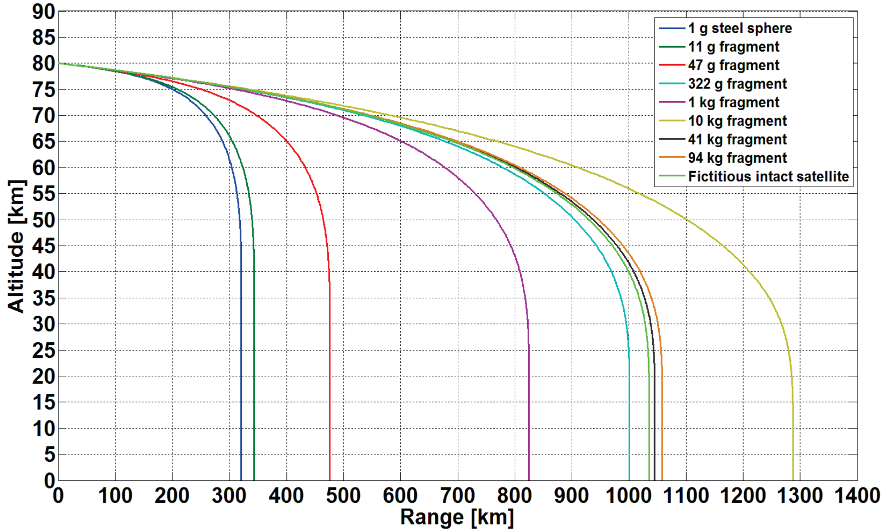
- **Only a few re-entry opportunities are typically included in the global uncertainty time window 3-4 days before re-entry**
- **For each of them a corresponding re-entry ground track, risk zone (up to a given altitude) and risk time window are computed**
- **The computed products maintain their intrinsic validity until the end, even if improvements are progressively possible: reduction of the cross-track safety margin; slight adjustment of the re-entry ground track**
- **Nearing the re-entry, a contraction of the risk zones is likely, but not an appreciable reduction and/or shift of the associated risk time windows (< 1-2 minutes)**

The most significant event occurring in the last few days, from the prediction point of view, is the progressive contraction of the global uncertainty time window as the orbital decay approaches

- **When a re-entry opportunity previously identified over the region of interest is left out of the shrinking global uncertainty window, such a possibility, and the corresponding risk zone and time window, can be finally discarded from the original alert list, *and this happens again and again during the last 3 days of satellite lifetime***
- **However, sometimes it is not possible to exclude any risk for an area of interest until the re-entry actually occurs**

Re-entry debris distribution

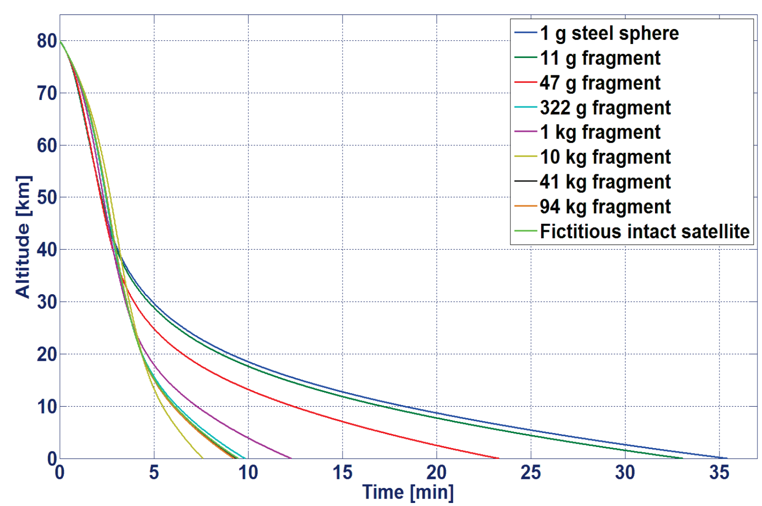




Downrange distribution of re-entry debris from the breakup altitude (80 km) to ground impact. In addition to realistic fragments, a 1 g steel sphere and a fictitious intact satellite of 1000 kg were considered as well

- The impact time dispersion among the surviving fragments in the 1 g – 100 kg mass range can be around 15-30 minutes
- Considering the relatively short time (2-5 minutes) spent by the faster fragments to fall through the airspace (from 15 km height to ground impact), a slight increase of the time dispersion window by the same amount can include the risk interval for overflying aircraft as well

- The surviving debris ground footprint is aligned with the re-entry trajectory and is typically 1000-2000 km long
- Often, *but not necessarily always*, heavy fragments fall first toward the forefoot
- Light fragments typically impact the ground, with a certain time delay, toward the heel of the debris footprint



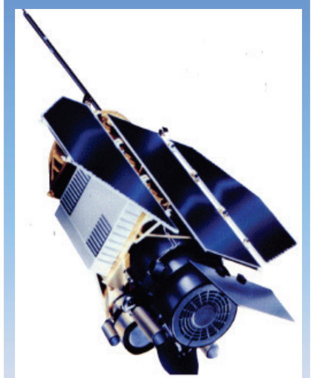
Time of flight of re-entry debris from the breakup altitude (80 km) to ground impact

Recent re-entry examples

**From September 2011 to November 2013
the re-entry of four decaying spacecraft was followed
for the Italian civil protection authorities**

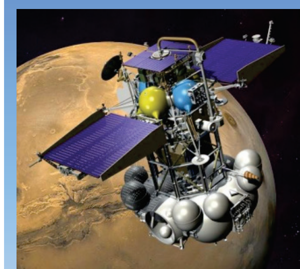
UARS

(5668 kg)



ROSAT

(2426 kg)



Phobos-Grunt

(13,535 kg; 2350 kg excluding the liquid propellant on board)

GOCE

(1002 kg)

- For UARS, a detailed re-entry risk assessment was carried out by NASA using ORSAT
- The fragmentation of the other three spacecraft was modeled in detail by Hyperschall Technologie Göttingen (HTG) using SCARAB
- Basic information with a varying degree of completeness and detail, concerning the fragments generated and their spread in ground impact time and footprint (down range and cross-track), was therefore available, or deduced, for the definition of the regional re-entry risk zones and the associated time windows

UARS & ROSAT re-entry

Last re-entry opportunity over Italy (descending central track) for UARS

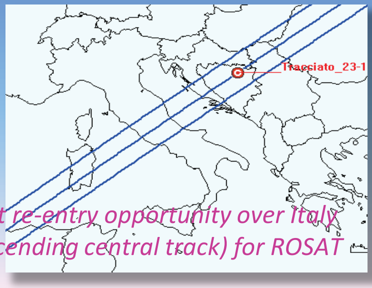
The risk zones and time windows for Italy were issued ~ 64 hours ahead of re-entry

The satellite re-entry tracks possibly affecting the Italian territory were 2 in a global uncertainty window 30 hours wide

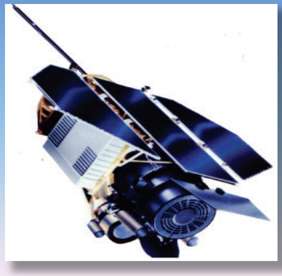
The risk time window associated to each track was 38 minutes, including the airspace up to the altitude of 10 km

The possible cross-track dispersion of the fragments was assumed to be ±100 km around the simulated re-entry tracks

The last "surviving" risk zone fell finally out of the global uncertainty window 5 hours before re-entry



Last re-entry opportunity over Italy (ascending central track) for ROSAT



The risk zones and time windows for Italy were issued ~ 88 hours ahead of re-entry

The satellite re-entry tracks possibly affecting the Italian territory were 5 in a global uncertainty window 51 hours wide

The risk time window associated to each track was 30 minutes, including the airspace up to the altitude of 10 km

The possible cross-track dispersion of the fragments was assumed to be ±90 km around the simulated re-entry tracks

The last "surviving" risk zone fell finally out of the global uncertainty window ~ 18.5 hours before re-entry

Phobos-Grunt & GOCE re-entry

Last re-entry opportunity over Italy (ascending central track) for Phobos-Grunt

Last re-entry opportunity grazing Italy (ascending central track) for GOCE

The risk zones and time windows for Italy were issued ~ 57 hours ahead of re-entry

The satellite re-entry tracks possibly affecting the Italian territory were 3 in a global uncertainty window 28 hours wide

The risk time window associated to each track was 30 minutes, including the airspace up to the altitude of 10 km

The possible cross-track dispersion of the fragments was assumed to be ±120 km around the simulated re-entry tracks

The last "surviving" risk zone remained in play until the very end, when it was confirmed that such expected pass over Europe had not occurred, being the probe re-entered before crossing the Atlantic Ocean

The risk zones and time windows for Italy were issued ~ 61 hours ahead of re-entry

The satellite re-entry tracks possibly affecting the Italian territory were 6 in a global uncertainty window 67 hours wide

The risk time window associated to each track was 40 minutes, including the airspace up to the altitude of 12 km

The possible cross-track dispersion of the fragments was assumed to be ±200 km around the simulated re-entry tracks

The last "surviving" risk zone fell finally out of the global uncertainty window ~ 14 hours before re-entry, thanks to a significant contraction (to ±120 km) of the ground safety swath

Conclusions

- Even though the re-entry predictions of uncontrolled satellites are intrinsically affected by substantial uncertainties until orbital decay, over the years a set of prediction products was specifically developed for the civil protection community and applications
- It is easily applicable to areas of 2000×2000 km^2, i.e. ten times those of a country like Italy, and consists of regional risk zones and associated time windows, which can be accurately defined at least 3-4 days ahead of re-entry
- Such information can be updated, if needed, for instance by reducing the surface of the risk zone associated with a certain re-entry opportunity, but in practice remains relatively stable and accurate until re-entry
- The main purpose of the subsequent re-entry predictions is instead checking if the identified regional risk zones and time windows are remaining or not inside the progressively updated and shrinking global uncertainty window
- If, finally, all of these risk zones move outside the global uncertainty window, any residual re-entry risk for the region of interest can be excluded; otherwise a risk zone identified at least three days in advance will remain alerted until the re-entry has occurred
- As demonstrated by the experience with the Italian civil protection authorities, these products are relatively easy to understand also for people not familiar with orbital dynamics. Moreover, they are timely, compact, unambiguous and remarkably stable, all qualities that make them very useful for civil protection applications