Italian National Research Council

Institute of Information Science and Technologies

GOCE REENTRY PREDICTIONS FOR THE ITALIAN CIVIL PROTECTION AUTHORITIES

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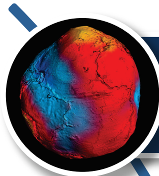
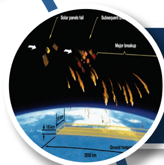
GOCE reentry captured from the Falkland Islands by Bill Chater on 11/11/2013 at 00:16 UTC

5th International GOCE User Workshop, Paris, France, 25-28 November 2014

OUTLINE

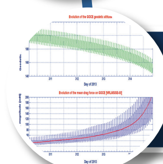


Gravity field and steady-state Ocean Circulation Explorer



Risk assessment
Boundaries of the risk time windows for Italy

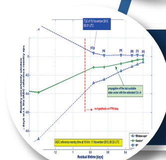
The peculiar nature & critical aspects of the GOCE reentry campaign



Evolution of the drag force on GOCE

REENTRY PREDICTIONS CAMPAIGN

Products for civil protection applications
Global reentry uncertainty windows



Nominal reentry epoch & $A \times C_D$ evolution
Parametric evaluation of nominal reentry epochs

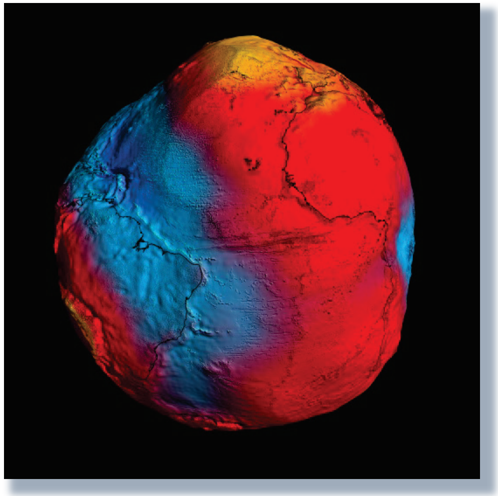
Possible reentry opportunities over Italy
Final global reentry ground track

GOCE

Gravity field and steady-state Ocean Circulation Explorer

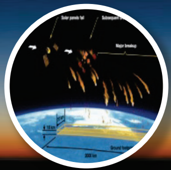
COMMON NAME	GOCE
LAUNCH DATE	17 March 2009, 14:21 UTC
US CATALOG NUMBER	34602
COSPAR ID	2009-013A
DRY MASS	1002 kg
SHAPE	Roughly cylindrical (Diameter: 1 m; Length: 5.3 m) with wing-shaped fins spanning 2 m

REENTRY EPOCH	US SSN	11 November 2013, 00:16 UTC [80 km]
	IADC	reference reentry time - 11 November 2013, 00:23 UTC [10 km]



- For more than four years GOCE mapped the geopotential with unrivalled accuracy and detail
- On 21 October 2013
  - The mission came to a natural end: *the low thrust ion propulsion motor, used to contrast the atmospheric drag, was automatically shut down when the pressure in the xenon propellant tank dropped below a critical threshold*
  - The satellite started its orbital decay phase

Risk assessment



A pre-launch destructive analysis was carried out for ESA by Hyperschall Technologie Göttingen (HTG) using the Space-Craft Atmospheric Re-entry and Aerothermal Break-up (SCARAB) software tool

- The beginning of the satellite fragmentation was predicted at an altitude of ~ 95 km and the end at ~ 35 km, but most of the debris generation was expected between 80 and 45 km
- Overall, 43 macroscopic fragments, totaling approximately 270 kg, were expected to survive reentry, hitting the ground along a 900 km footprint during a 17 minutes time interval
- The most massive fragment would have had a mass just below 95 kg

There were no hazardous materials on-board and, according to ESA, the components suspected to survive reentry were a tank and the magnetotorquers. The rest of the falling debris would have been just irregular fragments

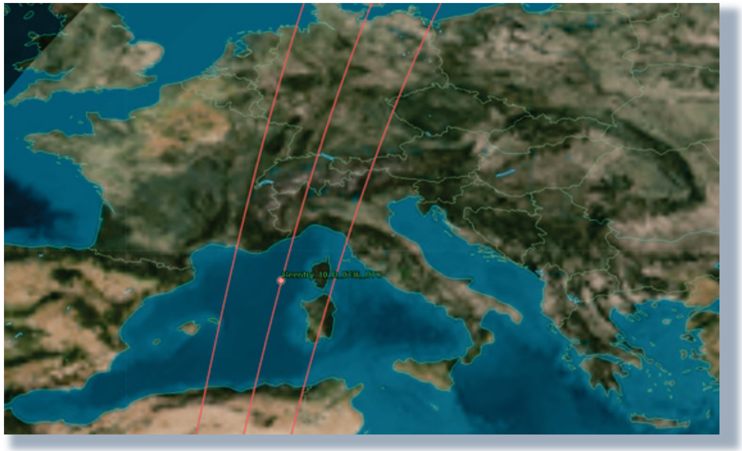
Even if not zero, the individual risk for any inhabitant of the Earth was very small: *65,000 times lower than being hit by lighting, or 1.5 million times lower than being killed in a home accident*

A minimum casualty expectancy (E_c) of ~ 0.0002 was estimated at ISTI/CNR implying a probability of ~ 1/5000 of causing 1 casualty over the whole world

Boundaries of the risk time windows for Italy

- The boundaries of the risk time windows valid for the Italian territory and airspace – *from the geodetic altitude of 12 km down to ground impact* – were obtained
    - by subtracting 10 minutes (lower bound)
    - and by adding 30 minutes (upper bound)

  to the simulated "fictitious" ground impacts times of the intact satellite, *conventionally assumed as reference to set the absolute scale of time*



These 40 minutes risk time windows would have been adequate to cover

- The impact time dispersion of the expected macroscopic fragments (17 minutes)
- The time needed to cross the national airspace from 12 km down to the ground
- The trajectory and propagation uncertainties
- The probable production of small slowly descending particles, not modeled by SCARAB, but possibly representing a marginal hazard for aircraft in flight

The peculiar nature of the GOCE reentry campaign

Fine-pointing mode (FPM) phase

- According to ESA information, once the fuel ran out, GOCE entered in “fine-pointing mode” (FPM), a phase of the orbital decay in which the satellite maintained a stable attitude by minimizing the drag force with $C_D \times A = 3.5\ \text{m}^2$

Expected duration of the FPM phase

- According to the pre-launch specifications the on-board attitude control system was expected to compensate the gravity gradient and the aerodynamic torques up to an average drag force along the orbit of 20 mN

Possible random tumbling attitude following the FPM stop

- Then the attitude control would have failed, making the reentry of GOCE totally uncontrolled and, according to simulations carried out by ESA, GOCE would have probably assumed a random tumbling attitude with a corresponding $C_D \times A = 11\ \text{m}^2$

Unexpected over-performance of the FPM controller

- Contrarily to any expectation, the attitude control system kept working nominally until reentry, even when the drag levels encountered exceeded 2000 mN, far beyond (> 100 times) the project specifications

- The peculiar nature of the GOCE reentry campaign – *sharing an uncontrolled orbital decay with a finely controlled attitude along the direction of the atmospheric drag* – made the reentry predictions for this satellite an interesting case study, in particular because nobody was able to say a priori if and when the attitude control would have failed leading to a random tumbling and to a sudden variation of the orbital decay rate

Critical aspects of the GOCE reentry campaign

- Therefore, even though the casualty expectancy for this reentry was just slightly above the internationally recognized alert threshold of 1/10,000, i.e. around 1/5000, it presented a number of challenges and opportunities, from the prediction and risk evaluation points of view, by reason of its peculiar nature

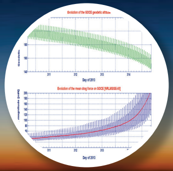
- Due to the unpredictability of the instant and altitude at which the attitude control system would have failed, the definition of reliable and conservative uncertainty windows was not easy, especially considering the critical use of this information for civil protection evaluations

- ISTI/CNR was in charge of reentry predictions for the Italian civil protection authorities, monitoring also the satellite decay in the frame of an international reentry campaign promoted by the Inter-Agency Space Debris Coordination Committee (IADC)

- Predictions of the "nominal" reentry time with associated uncertainty time windows were carried out in the framework of the IADC campaign

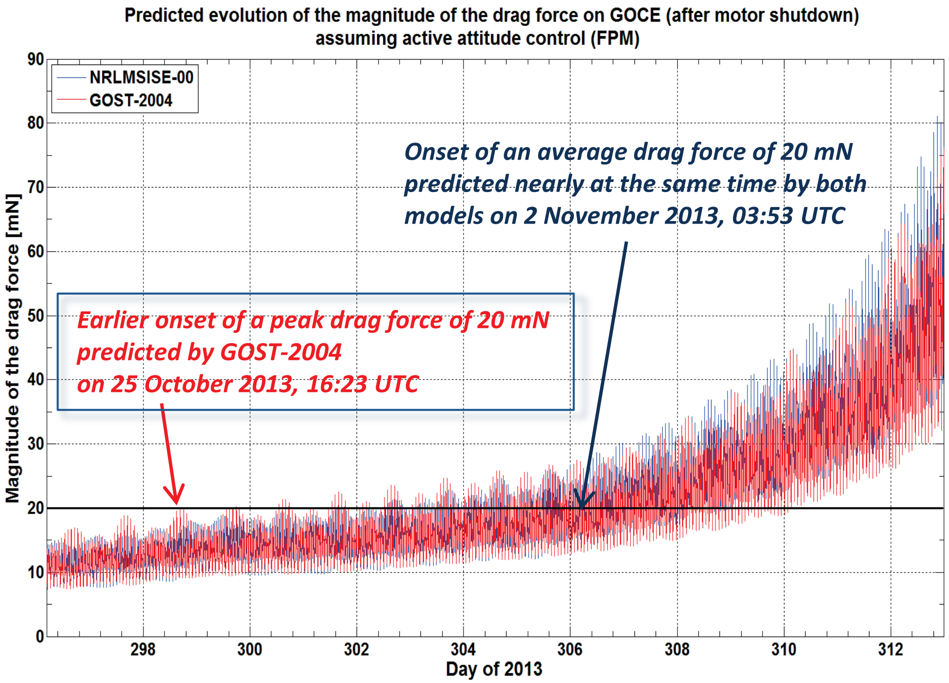
- A set of tailored products was developed for the Italian civil protection authorities to identify, starting 3 days before reentry and in the area of interest, risk zones and corresponding alert time windows in the event of undue debris impact hazard on the national territory

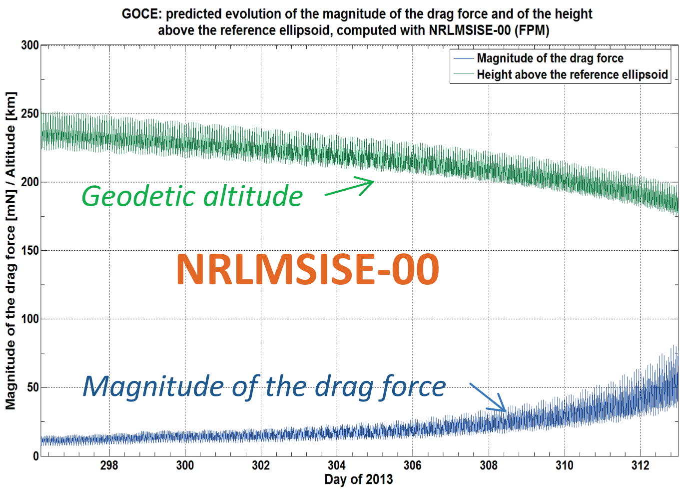
Evolution of the drag force [1]



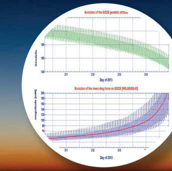
- The evolution of the drag force on GOCE was computed using an upgraded version of the ISTI/CNR SATellite Reentry Analysis Program (SATRAP) software tool and assuming a fine-pointing attitude control
- For the 1st reentry prediction, issued on 23 October 2013, two atmospheric density models were compared: the American NRLMSISE-00 and the Russian GOST-2004; both models predicted the reaching of a mean drag force of 20 mN along the GOCE orbit around 1-2 November 2013

- The knowledge of the drag force evolution, with particular attention to the epoch associated with an average drag force along the orbit expected to overcome the FPM controller, or that corresponding to the earliest onset of a peak drag force with the same magnitude, was of value to elaborate reasonably conservative criteria for the early definition of the reentry uncertainty windows





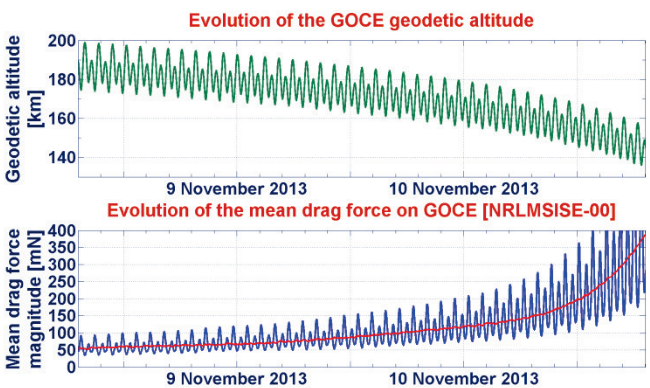
Considering the very good agreement between the two models, only one of them (NRLMSISE-00) was used during the GOCE reentry campaign



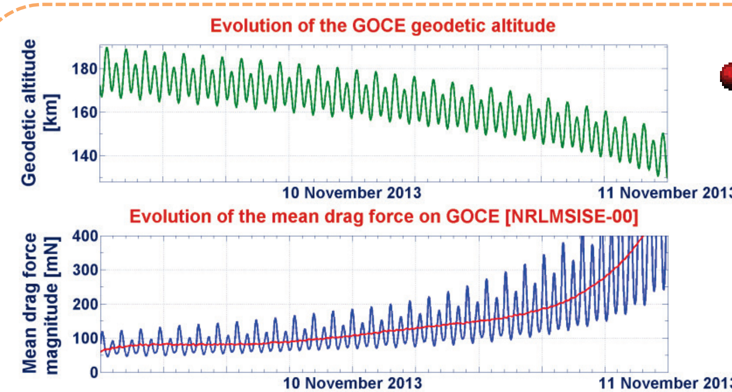
Evolution of the drag force [2]

- The constant monitoring all over the reentry campaign of the drag levels encountered permitted
  I. To verify the very impressive performance of the GOCE attitude control system
  II. To test the goodness of the simulation results obtained with NRLMSISE-00

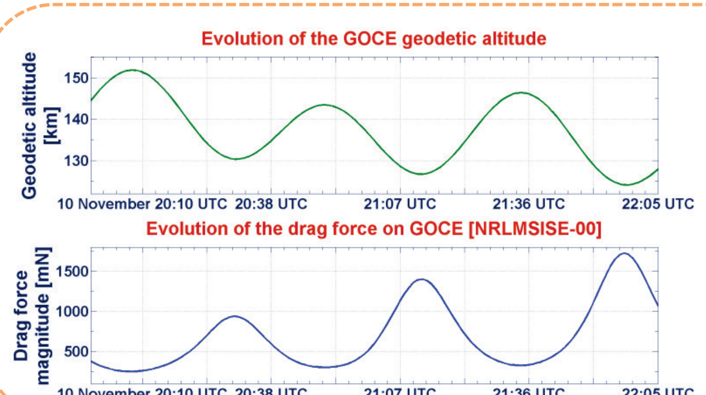
- A very good agreement was found between measured (*plots provided by ESA, for the instantaneous drag and the average drag over one orbit, through the IADC Reentry Events Database*) and simulated drag force, proving that even when it exceeded 20 mN the satellite kept working in FPM



- At the beginning of 8 November 2013, the mean drag force exceeded 50 mN

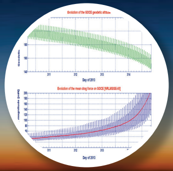


- Coming near to 100 mN on 10 November



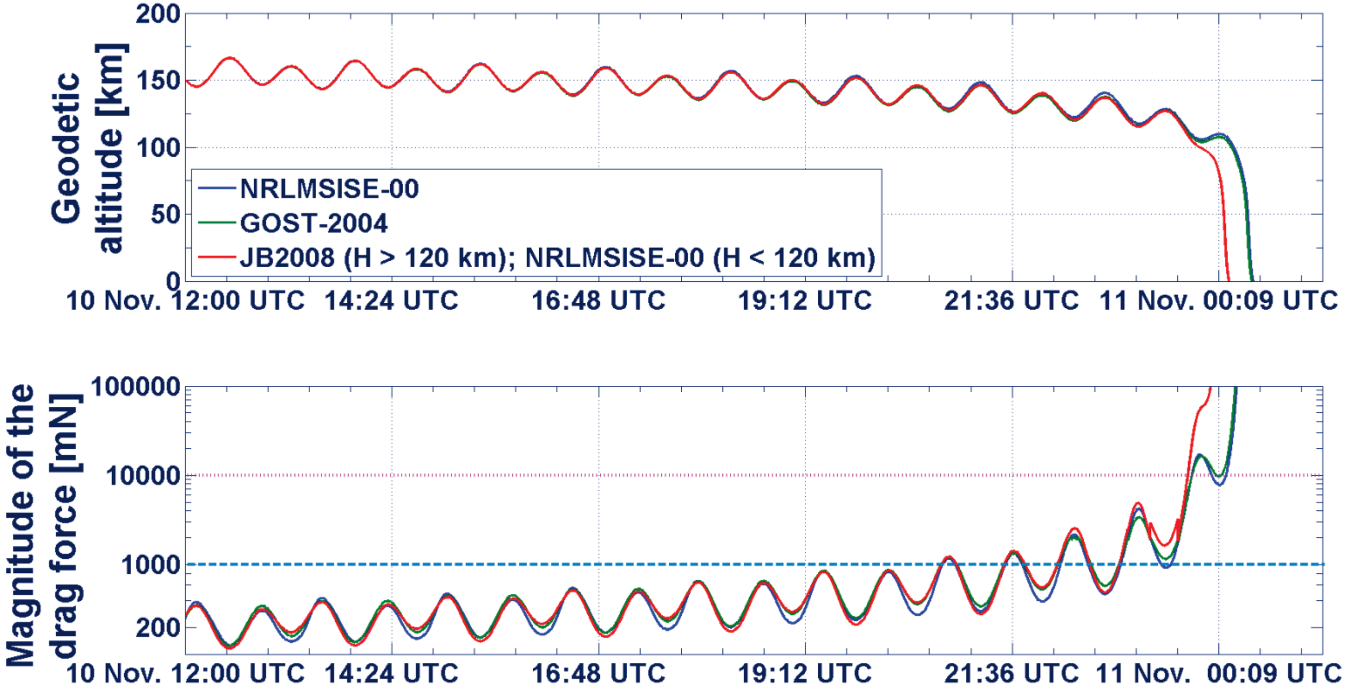
- Exceeding 1000 mN a few hours ahead of reentry

Evolution of the drag force [3]



- The evolution of the drag force encountered by the satellite just before reentry was also estimated, in a post-event analysis, using the thermospheric density models NRLMSISE-00, GOST-2004 and JB2008

- Apart from the observed very good agreement among the outputs obtained by different atmospheric density models, the results displayed once again the extraordinary level of over-performance of the attitude control system, still working at drag levels of more than 1000 mN, and operational until reentry, with limiting drag forces probably exceeding 2000 mN



THE REENTRY PREDICTIONS CAMPAIGN

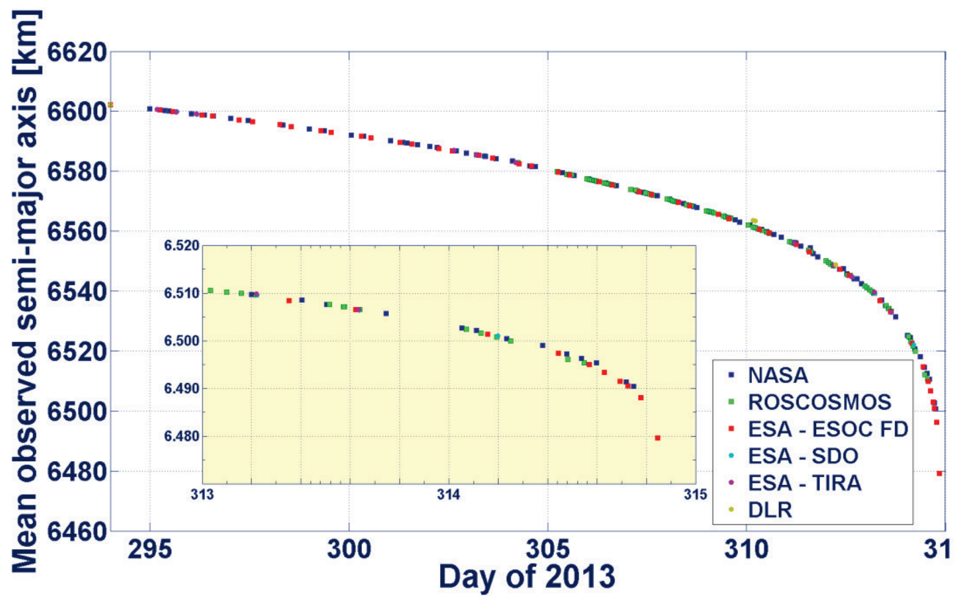
22 REENTRY PREDICTIONS WERE CARRIED OUT FOR THE GOCE REENTRY CAMPAIGN

The first was issued by ISTI/CNR on 23 October 2013, followed by six others performed during the so-called "test and analysis phase" (23-31 October 2013). Predictions 8-14 were issued during the "operational phase" (2-8 November 2013), while predictions 15-22 were carried out in the "final phase" (9-10 November 2013)

Each reentry prediction involved the following computational tasks

I. Estimation of the product $A \times C_D$, by minimizing the root mean square residuals between observed and computed mean semi-major axis decay

II. Propagation of the last available Two-Line Elements (TLE) set, using the estimated $A \times C_D$, to assess the evolution of the drag force acting on the satellite under the assumption of an operational fine-pointing mode



III. Computation of the "nominal" reentry epoch, based on a set of hypotheses evolving in accordance with the new data available on the performance of the attitude control system

IV. Definition and computation of a global reentry uncertainty time window associated with each reentry prediction

V. Representation of the ground tracks corresponding to the current global uncertainty time window, during the last 3 days before reentry

Products for civil protection applications [1]

- However, the previous reentry prediction standard products
- Were of no, or very limited, use for civil protection applications

Nominal decay forecast

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

Global uncertainty time window

- Provided relevant information, identifying the time interval in which the reentry could be expected, somewhere in the world; but this interval remained too large until reentry, so it was not possible to devise and apply practical precautionary civil protection measures based on it

Sub-satellite ground tracks

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

- The locations possibly at risk in a given area embracing Italy could not be identified reasonably ahead of reentry with such information

Products for civil protection applications [2]

To solve these problems, a novel targeted approach was devised, implemented and applied in Italy to real reentry campaigns since the orbital decay of the BeppoSAX satellite in 2003

- Our approach was based on the simple remark that, for each overflown location included in the global uncertainty time window, reentry or debris ground impact was possible, in principle, but not certain; however, in each place, the eventual reentry or impact would have occurred only during a specific and quite accurate risk time window, which could be therefore used to plan risk mitigation measures on the ground and in the overhead space

- During the GOCE reentry campaign, it consisted in making available, *starting 3 days before the final decay*

  I. The possible reentry ground track
  II. The associated risk zone (up to a given altitude)
  III. The risk time window

  for each reentry opportunity over Italy included in the current global uncertainty time window

- Providing such information a few days in advance was necessary to make possible the appropriate civil protection planning in the areas potentially affected and the reliable identification of the areas excluded from any risk

Products for civil protection applications [3]

- FOR EACH REENTRY OPPORTUNITY OVER THE NATIONAL TERRITORY, INCLUDED IN THE CURRENT GLOBAL UNCERTAINTY TIME WINDOW

  I. The ground impact time of the simulated intact satellite was predicted first

  II. Then the risk time window was defined with respect to this time, i.e. by subtracting 10 minutes and by adding 30 minutes to the reference time thereof

- The ground impact time

  - was identified by iteratively modifying by a small amount the nominal product of the terms used to model the aerodynamic drag, i.e. drag coefficient, satellite cross-sectional drag area and atmospheric density, for instance C_D or A

  - resulted to be very accurate due to the almost exact synchronization of the satellite dynamical evolution and Earth rotation, in such a way to obtain a reentry just over Italy

- Considering a region sufficiently wide to include Italy and a significant portion of the surrounding lands and seas (e.g. almost 2000 × 2000 km^2), each possible reentry track was accurately modeled by simulating just one ground impact, with a maximum timing error of ±2 minutes, deemed acceptable if compared with the flight times dispersion of the macroscopic fragments

Global reentry uncertainty windows [1]

- Due to the active control system and to the unpredictability of the instant and altitude at which the system would have failed, it was not possible to adopt standard criteria, based on previous experiences, to define the uncertainty reentry windows

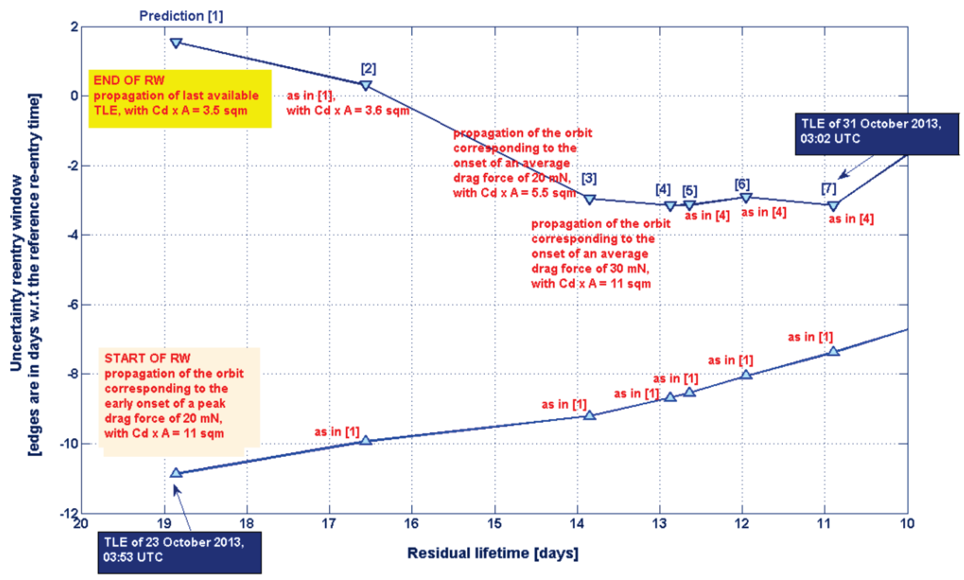
- However, after an initial period of test and analysis till the end of October 2013, in which only the opening of the window was of importance, *to at least exclude an early reentry before a given epoch*, reasonable conservative criteria were elaborated and applied, with good and consistent results through the end of the campaign

- These criteria were mainly based on the uncertainty affecting the duration of the FPM flight phase and depended as well on the information received by ESA and the acquaintance gained meanwhile through the monitoring of the drag levels and satellite orbital decay

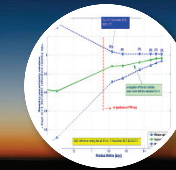
DURING THE TEST AND ANALYSIS PHASE (23-31 OCTOBER 2013)

The conservative opening of the reentry window was obtained by propagating, up to the IADC reentry conventional altitude of 10 km, the orbit corresponding to the earliest onset of a peak drag force of 20 mN, assuming the loss of attitude control and $A \times C_D = 11\ m^2$

The definition of the window closure changed instead during this phase, trying to restrain it in order to reduce the time interval of interest



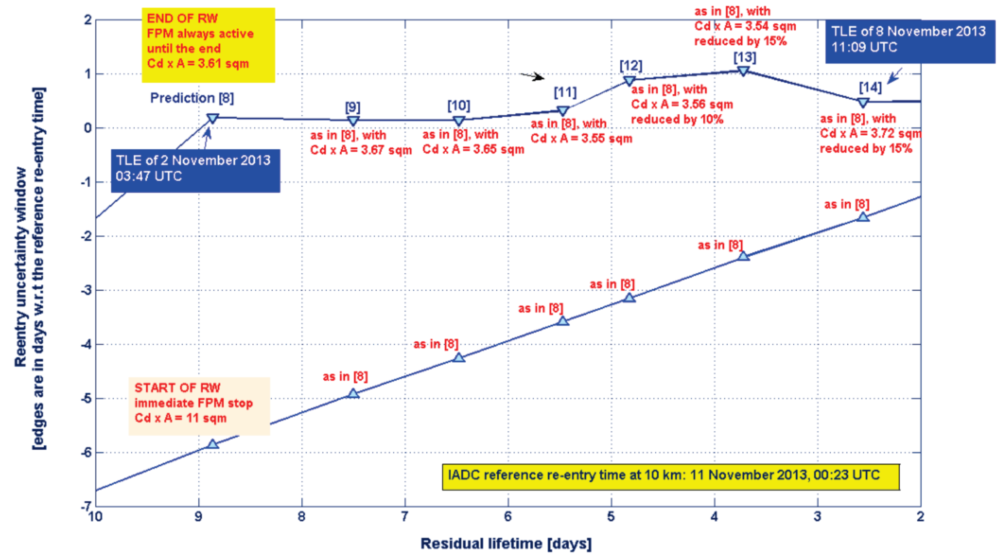
Global reentry uncertainty windows [2]

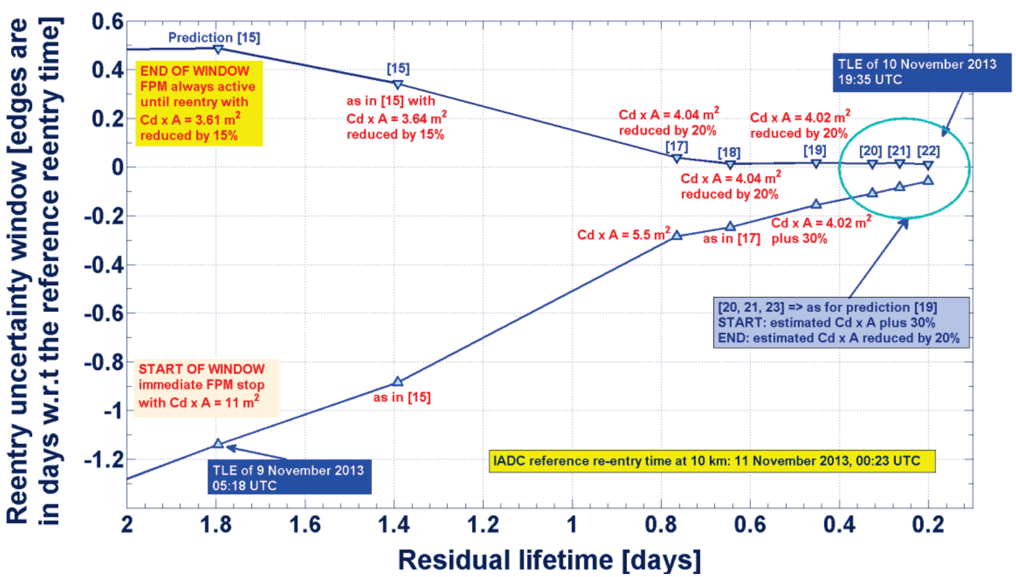


IN THE OPERATIONAL PHASE (2-8 NOVEMBER 2013)

The conservative start of the reentry window was computed by assuming an immediate stop of the FPM and then a sudden random tumbling with $A \times C_D = 11\ m^2$

For the closure, the FPM was considered to be active until the very end, with the estimated $A \times C_D$ reduced by 10-15%, in order to take into account a possible decrease of the drag coefficient at lower altitudes

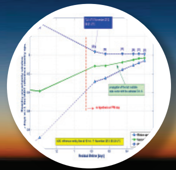




IN THE FINAL PHASE (9-10 NOVEMBER 2013)

And only for the last six predictions, standard criteria to define the uncertainty window, varying by a given percentage the product $A \times C_D$, were applied

Estimated nominal reentry epoch



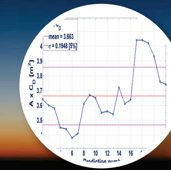
Due to the significant uncertainty surrounding the end of the FPM flight phase

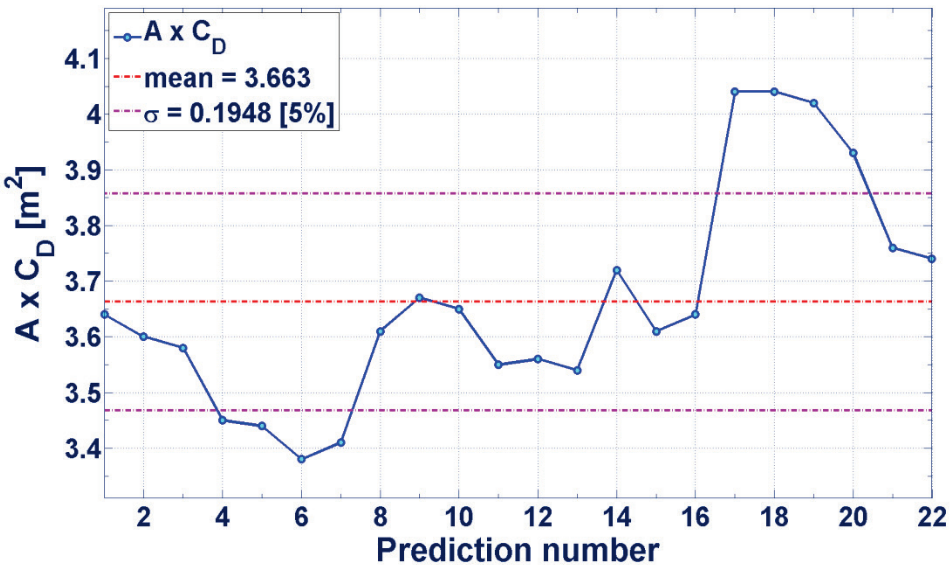
The nominal reentry forecasts were highly speculative, just a guess exercise

- For predictions 1-16, they were obtained by propagating the orbit corresponding to the onset of the average drag force expected to cause the FPM stop, e.g. 20 mN for prediction 1, 150 mN for prediction 16
- Only the last six nominal reentry times (predictions 17-22) were computed with no assumption on the duration of the FPM phase, but just propagating the last available orbital elements with the estimated $A \times C_D$

	Average drag force leading to the FPM failure	NOMINAL REENTRY EPOCH yyyy-mm-dd	hh:mm:ss
1	20 mN	2013-11-08	16:03:00
2	20 mN	2013-11-04	22:05:45
3	20 mN	2013-11-04	19:59:16
4	20 mN	2013-11-04	11:11:07
5	20 mN	2013-11-04	11:35:00
6	20 mN	2013-11-04	16:38:59
7	20 mN	2013-11-04	10:04:57
8	30 mN	2013-11-07	05:54:50
9	30 mN	2013-11-07	05:34:17
10	35 mN	2013-11-07	21:50:16
11	45 mN	2013-11-08	20:56:43
12	100 mN	2013-11-10	11:16:14
13	150 mN	2013-11-10	20:53:30
14	150 mN	2013-11-10	13:10:13
15	150 mN	2013-11-10	16:15:47
16	150 mN	2013-11-10	15:07:08
	$A \times C_D$	yyyy-mm-dd	hh:mm:ss
17	4.04 m^2	2013-11-10	21:37:15
18	4.04 m^2	2013-11-10	21:40:56
19	4.02 m^2	2013-11-10	22:34:00
20	3.93 m^2	2013-11-10	23:13:00
21	3.76 m^2	2013-11-10	23:32:00
22	3.74 m^2	2013-11-10	23:43:00

Estimated $A \times C_D$

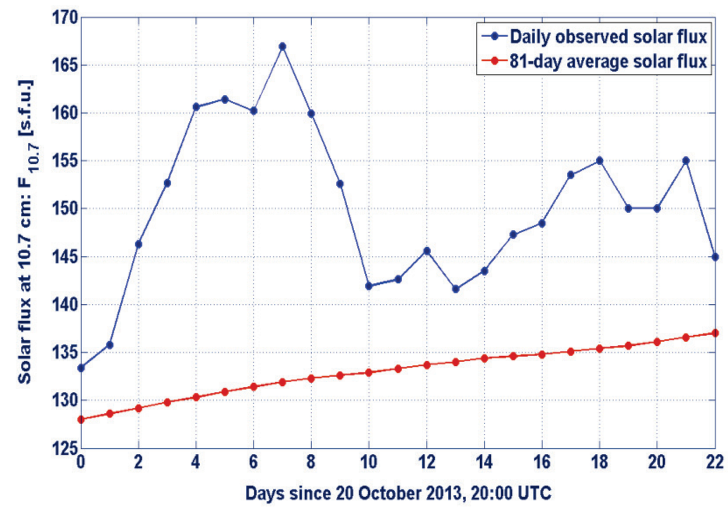




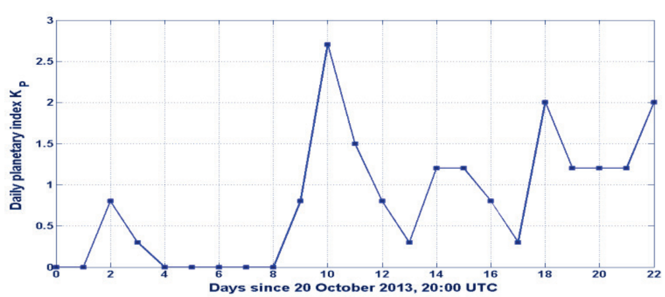
Evolution of the GOCE $A \times C_D$ product during the reentry campaign

- **The difference between the mean estimated value of the ballistic coefficient ($A \times C_D$ = 3.663 ± 0.195 m²) and the corresponding value computed for the FPM phase ($A \times C_D$ = 3.5 m², according to ESA analyses) was within the standard deviation (±5%)**

- **The GOCE reentry campaign offered as well the opportunity to gain insight into the accuracy of the air density model used, confirming very good performances of NRLMSISE-00 also for altitudes below 200 km, at least with the solar and geomagnetic conditions prevailing during the exercise**



$F_{10.7}$ cm solar flux during the GOCE reentry



K_p index during the GOCE reentry

Parametric evaluation of nominal reentry epochs

Detailed parametric analyses were carried out during the GOCE reentry campaign (issued on: 31 October, 5, 7 and 9 November 2013) to explore the full set of possibilities, including also very low probability outcomes, according to the available information received from ESA

FPM failure	Nominal Reentry Epoch at 10 km
Immediate	3 Nov 2013, 15:22 UTC
20 mN	4 Nov 2013, 10:05 UTC
21 mN	4 Nov 2013, 22:17 UTC
22 mN	5 Nov 2013, 18:14 UTC
23 mN	6 Nov 2013, 05:06 UTC
24 mN	6 Nov 2013, 13:23 UTC
25 mN	6 Nov 2013, 20:00 UTC
30 mN	7 Nov 2013, 20:47 UTC
40 mN	9 Nov 2013, 00:32 UTC
45 mN	9 Nov 2013, 10:11 UTC
50 mN	9 Nov 2013, 18:11 UTC
Always active	11 Nov 2013, 12:40 UTC

Issued on 31 October 2013

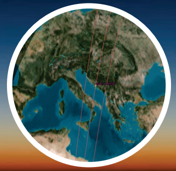
At that point the analysis could only exclude a GOCE reentry before

FPM failure	Nominal Reentry at 10 km
Immediate	8 Nov. 2013, 14:51 UTC
50 mN	9 Nov. 2013, 04:51 UTC
100 mN	10 Nov. 2013, 11:55 UTC
150 mN	10 Nov. 2013, 20:53 UTC
200 mN	11 Nov. 2013, 00:32 UTC
Always active	11 Nov. 2013, 08:27 UTC

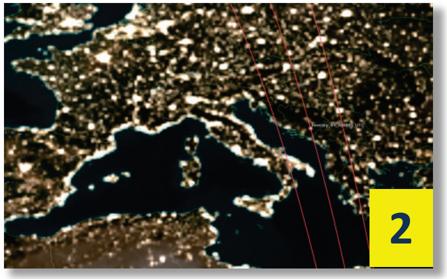
Issued on 7 November 2013

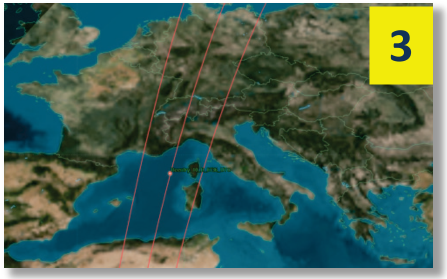
From all these analyses, it was evident the extreme sensitivity of the nominal reentry epoch to the exact value of the drag force able to overwhelm the GOCE attitude control system

Possible reentry opportunities over Italy [1]

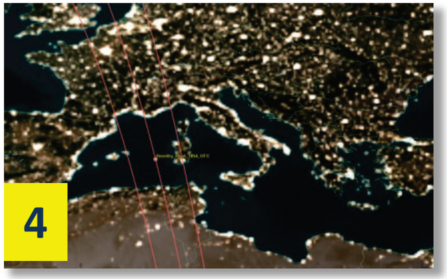


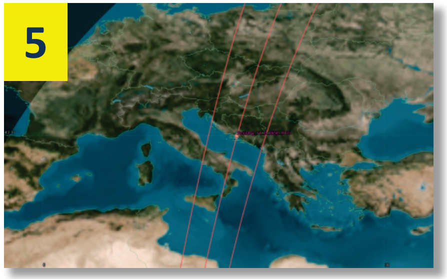
- In the last three days before reentry, the attention was focused on a specific area of the planet embracing Italy, so as to allow the civil protection authorities to plan and prepare appropriate risk mitigation measures for the zones potentially affected by a debris fall
- This was realized by simulating reentries over Italy, in order to obtain quite accurate ground tracks, debris swaths and air space crossing time windows associated with the critical passes over the national territory still included in the current global uncertainty windows
- The risk zones and time windows for Italy were first issued around 61 hours ahead of reentry; at that time the global uncertainty window was 67 hours wide and there were still six reentry opportunities possibly affecting the Italian territory, each with an associated risk time window of 40 minutes, including the airspace crossing, from 12 km to ground impact





No.	Day	Opening	Closure
1	9 Nov. (descending)	06:37 UTC	07:17 UTC
2	9 Nov. (ascending)	17:55 UTC	18:35 UTC
3	10 Nov. (descending)	07:26 UTC	08:06 UTC
4	10 Nov. (ascending)	18:44 UTC	19:24 UTC
5	11 Nov. (descending)	06:48 UTC	07:28 UTC
6	11 Nov. (ascending)	18:10 UTC	18:50 UTC



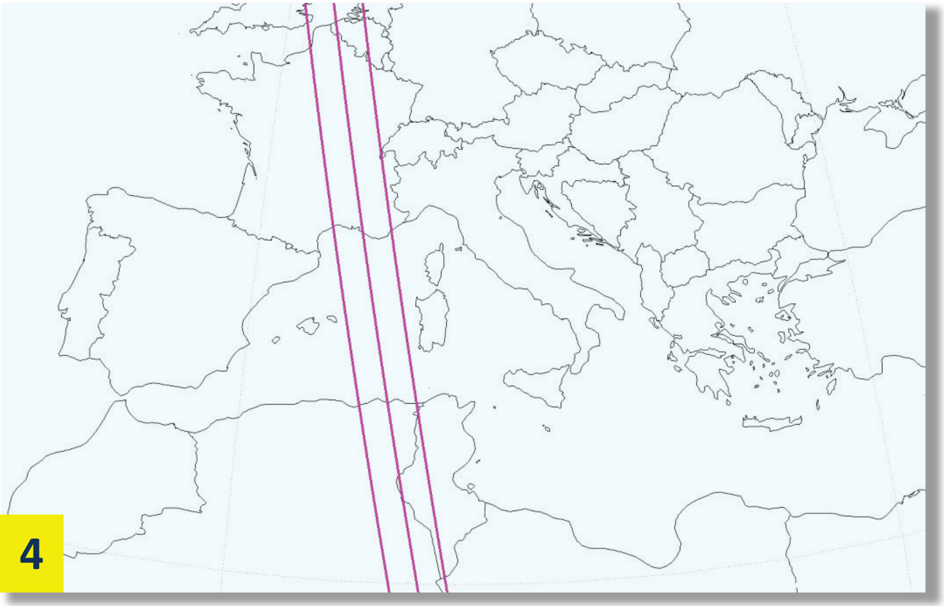


Possible reentry opportunities over Italy [2]

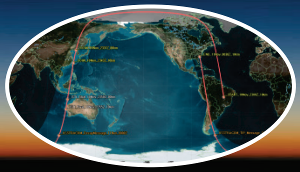
- Based on the information available, implying a maximum cross-track dispersion of the macroscopic fragments of ±15 km, and taking into account the uncertainty surrounding the actual endurance of the spacecraft active attitude control system, in addition to the possible cross-track reentry trajectory errors and wind effects on the smallest relevant particles, an initial, and very conservative, ground safety swath of ±200 km around the computed reentry tracks was assumed

- Approaching the orbital decay, as the global uncertainty window underwent its natural contraction, the number of reentry opportunities over Italy was progressively reduced
  - To four at minus 56 hours
  - To three at minus 40 hours
  - To only two at minus 25 hours, *when the global uncertainty window had shrunk to 23.5 hours*

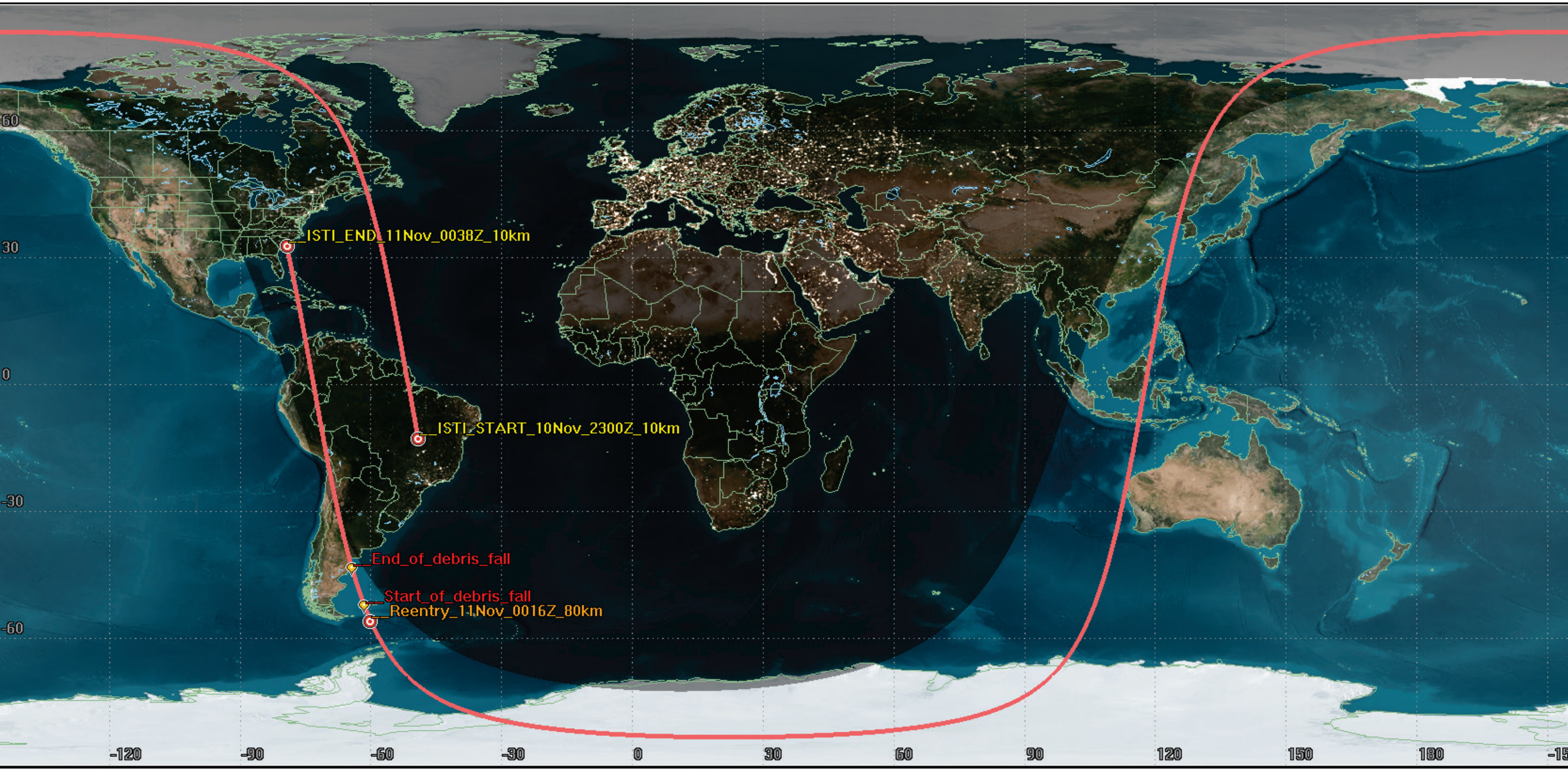
The last opportunity (No. 4) was finally excluded 14 hours before reentry
thanks to a significant contraction (to ±120 km) of the ground safety swath, which previously had included north-western Italy, close to the border with France, and western Sardinia



Final global reentry ground track



The final global ground track associated with the last reentry prediction uncertainty was issued by ISTI/CNR to IADC approximately 4 hours before reentry. The GOCE fragments eventually plunged into the Southern Atlantic Ocean, between the Falkland Islands and the coast of Argentina, on 11 November 2013, between 00:24 and 00:40 UTC.



Conclusions

- The GOCE reentry predictions campaign was quite peculiar, because the satellite attitude was controlled, and it was not possible to predict a priori if and when the system would have failed
- Having known since the beginning the extraordinary level of over-performance of the attitude control system, the nominal reentry epoch would have been consistently predicted with a much better residual percentage error
- However, being charged with civil protection responsibilities, much more important was the definition of consistent and conservative uncertainty windows (the “nominal” reentry epoch is not useful for civil protection applications)
- After an initial analysis phase (23-31 October 2013), in order to test the suitability and reliability of uncertainty windows definition, reasonably conservative criteria were elaborated and applied (1-10 November), with good and consistent results through the end of the campaign
- Based on the progressively shrinking global uncertainty window, the last (quite marginal) reentry opportunity over Italy was excluded 14 hours before reentry
- The GOCE surviving debris, according to the latest observations, sank into the Southern Atlantic Ocean, between the Falkland Islands and the coast of Argentina