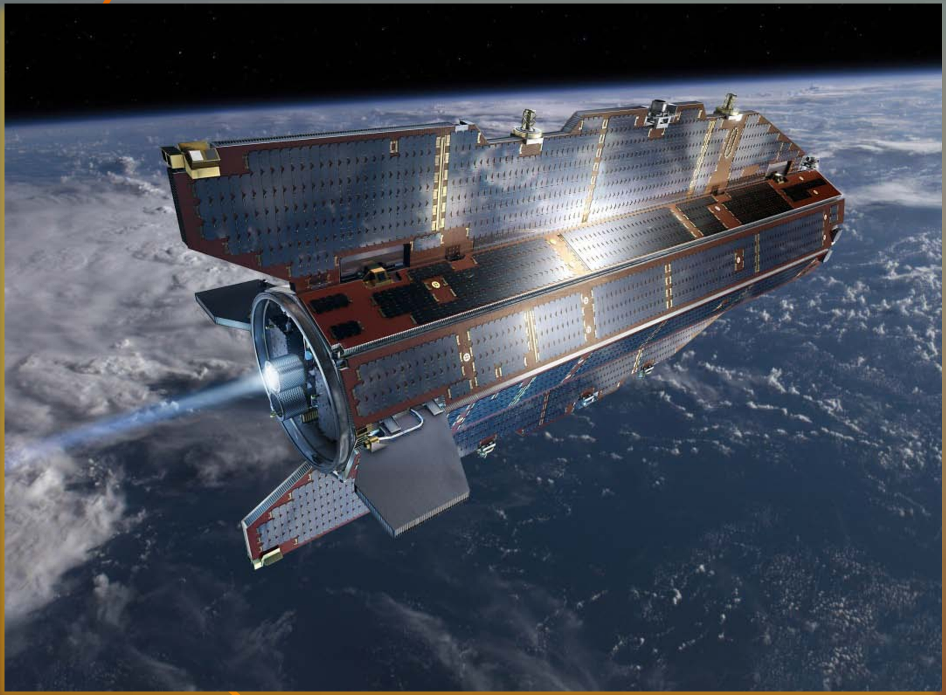
Italian National Research Council

Institute of Information Science and Technologies



ORBITAL DECAY ANALYSIS REENTRY PREDICTIONS AND RISK ASSESSMENT FOR THE GOCE SATELLITE

Carmen Pardini & Luciano Anselmo

Space Flight Dynamics Laboratory
ISTI-CNR, Pisa, Italy

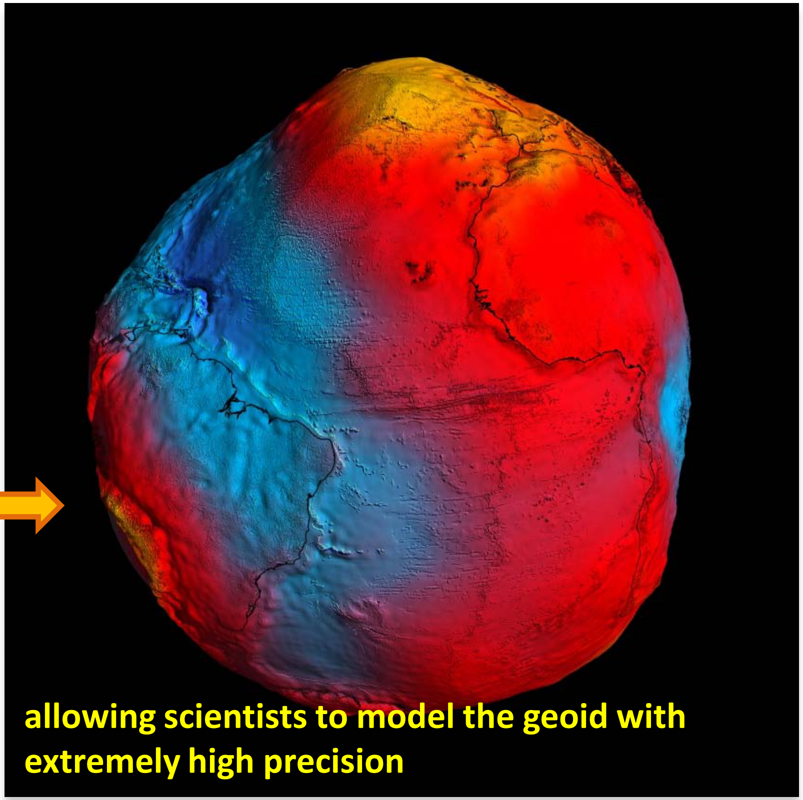
40th COSPAR Scientific Assembly, Moscow, Russia, 2-10 August 2014

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 DATE	11 November 2013, 00:16 UTC [80 km]

- For more than four years GOCE has mapped the geopotential with unrivalled accuracy and detail



New GOCE geoid

Released on 28/03/2011, ©ESA/HPF/DLR

- On 21 October 2013
  - <u>The mission came to a natural end</u>: *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*
  - <u>The satellite started its orbital decay phase</u>

Risk assessment

GOCE was the first uncontrolled reentry of an ESA satellite since 1987

A DESTRUCTIVE REENTRY ANALYSIS WAS CARRIED OUT BY HTG FOR ESA USING SCARAB

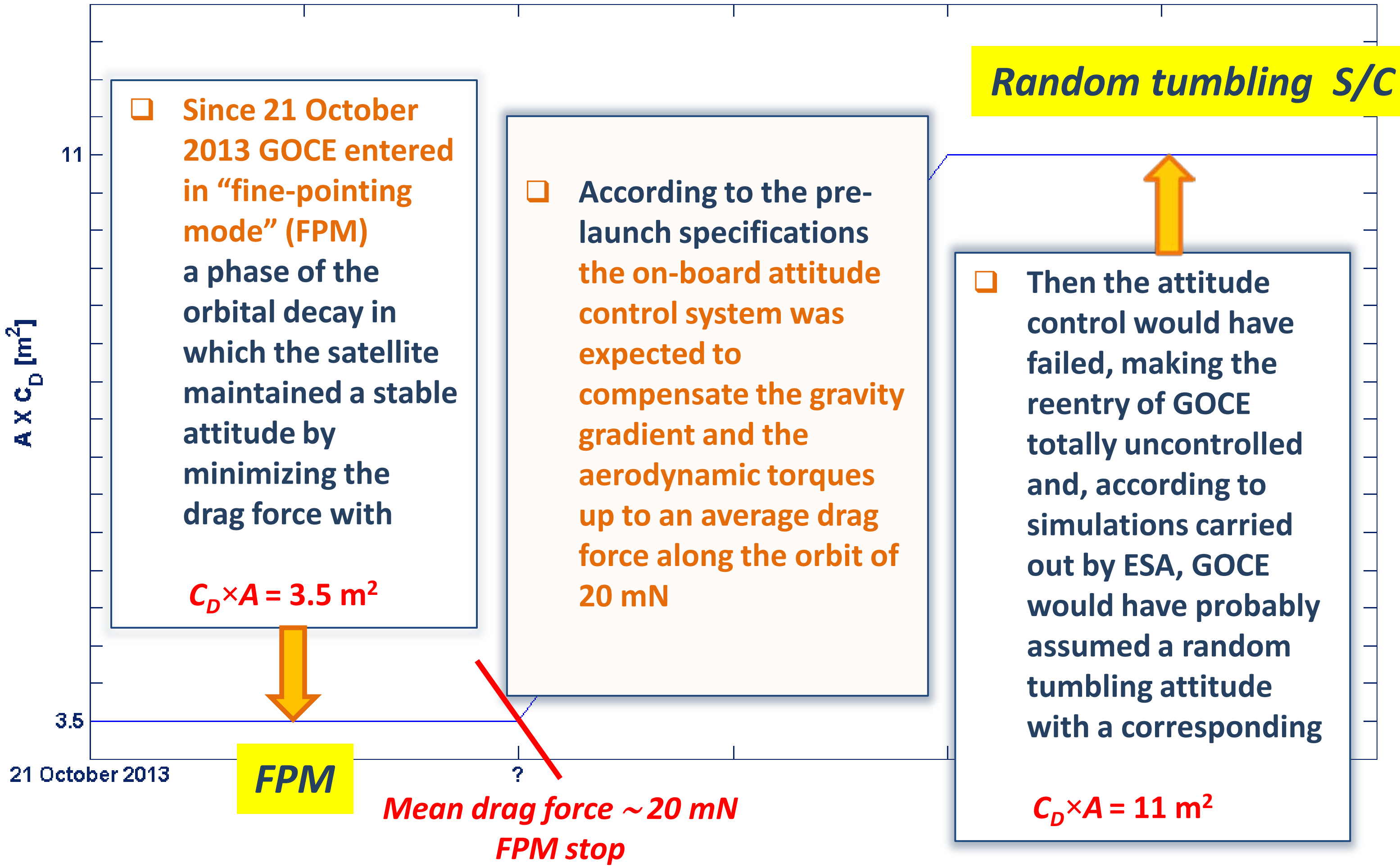
- The beginning of the satellite fragmentation was predicted at an altitude of ~ 95 km and the end at ~ 35 km, but most of the debris generation was expected between 80 and 45 km
- Overall, 43 macroscopic fragments, totaling approximately 270 kg, were expected to survive reentry, hitting the ground along 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

No official quantitative statement concerning the risk represented by the uncontrolled reentry of GOCE was issued by ESA. 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 casualty over the whole world of at least 1/5000

Expected timeline of the events



- Since 21 October 2013 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

  $C_D \times A = 3.5\ m^2$

- 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

- 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

  $C_D \times A = 11\ m^2$

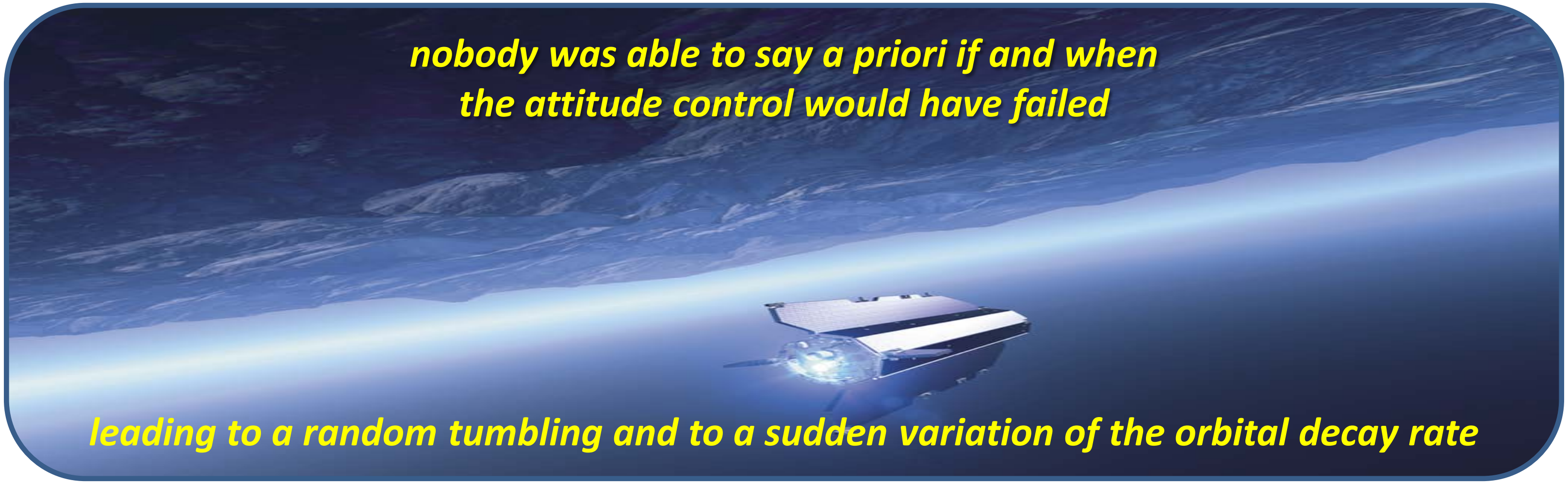
- With such an attitude and the prevailing thermospheric conditions, the satellite should have remained in orbit for a few days after the end of the FPM phase

Peculiar nature of the GOCE reentry

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

- "S/C operations proceeded up to 1.5 hours before re-entry, with the last ground contact at KSAT's Troll Station in Antarctica on 10/11/2013 at 22:43 UTC"
  [*GOCE End-of-Mission Operations Report, issued by ESA on 07/02/2014*]

- 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



Critical aspects of the GOCE reentry campaign

<u>ISTI/CNR was in charge of reentry predictions for</u>

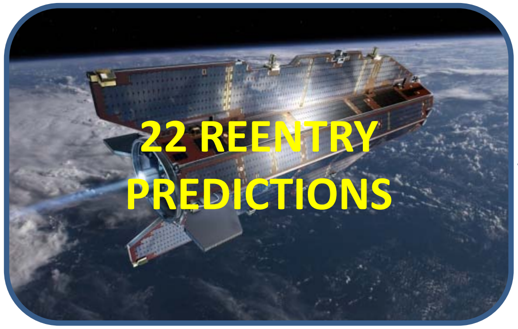
- The Italian Space Agency (ASI)
- The Italian Civil Protection Department
- The Inter-Agency Space Debris Coordination Committee (IADC) – ASI Technical Contact Point

- Considering the peculiar nature of the GOCE reentry, the definition of reliable uncertainty windows was not easy, in particular taking into account the critical use of this information for civil protection evaluations

- Due to the active attitude 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 [23 – 31 October 2013] – *in which only the opening of the window was of importance to exclude the reentry until a given epoch* – reasonably conservative criteria, mainly based on the uncertainty affecting the duration of the FPM flight phase, were elaborated and applied, with good and consistent results through the end of the campaign

Main computational tasks for the GOCE reentry campaign



- **Predictions 1 – 7** — TEST & ANALYSIS PHASE
  TLEs: 23 October 2013, 03:53 UTC – 31 October 2013, 03:02 UTC
- **Predictions 8 – 14** — OPERATIONAL PHASE
  TLEs: 2 November 2013, 03:47 UTC – 8 November 2013, 11:09 UTC
- **Predictions 15 – 22** — FINAL PHASE
  TLEs: 9 November 2013, 05:18 UTC – 10 November 2013, 19:35 UTC

I. Estimation of $C_D \times A$ by minimizing the root mean squares residuals between observed and computed mean semi-major axis decay [ISTI/CNR CDFIT tool]

II. Propagation of the last available two-line elements set, using the estimated "$C_D \times A$", to assess the evolution of the magnitude of the drag force acting on the satellite under the assumption of an operational fine-pointing mode [ISTI/CNR SATRAP tool]

III. Computation of the "nominal" reentry epoch [SATRAP tool]

IV. Definition and computation of the reentry uncertainty windows during the test, operational and final phase

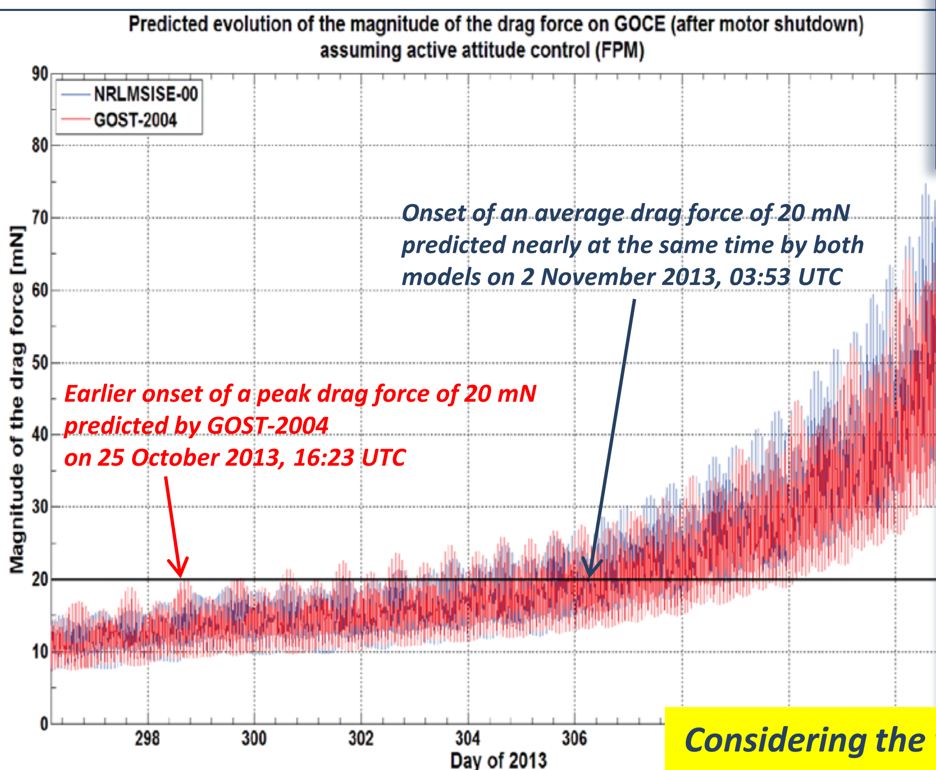
V. Definition of the risk time windows for Italy

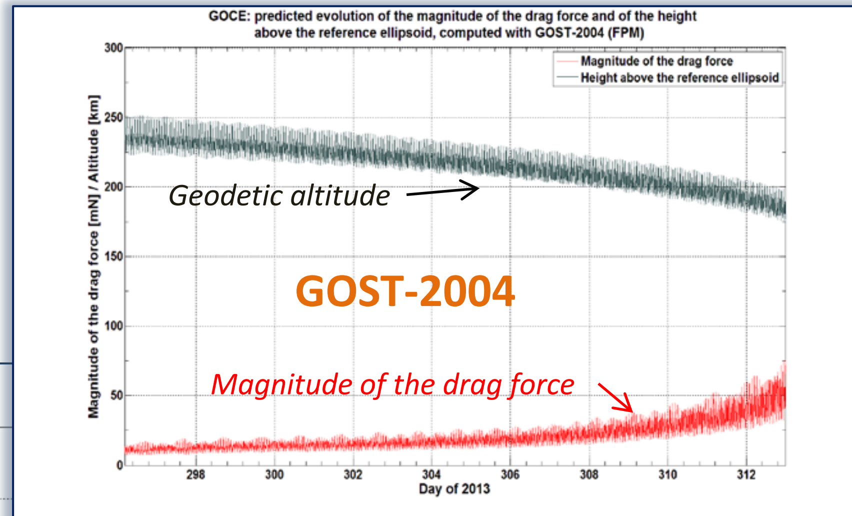
VI. Identification of possible reentry opportunities and ground tracks over Italy during the last 2-3 days preceding the reentry

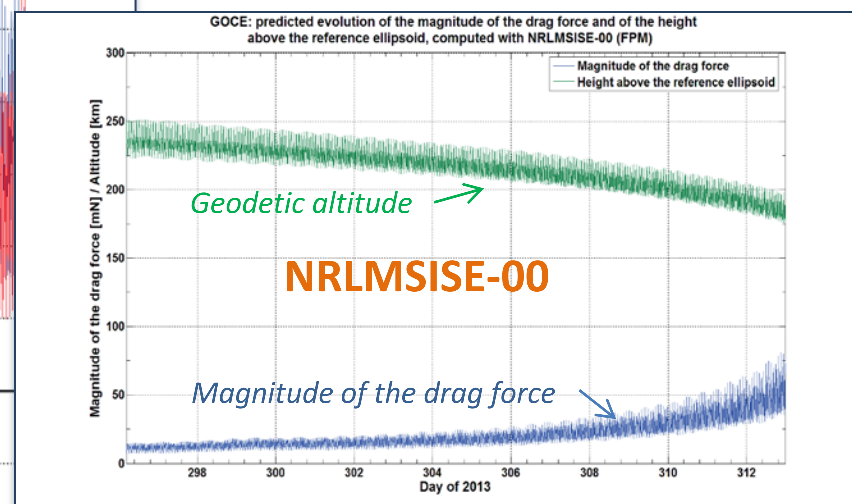
Evolution of the drag force predicted with two atmospheric density models

For the 1st reentry prediction, issued on 23 October 2013, two atmospheric density models were compared

- The atmospheric density models, **NRLMSISE-00** and **GOST-2004**, predicted the reaching of a mean drag force of 20 mN along the GOCE orbit around 1-2 November 2013







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

Early definition of a reentry uncertainty window
[2nd prediction issued on 25 October 2013]

The last available two-line elements set (*25 October 2013, 10:55 UTC*) was propagated using the estimated $C_D \times A$ = 3.60 m^2 and the NRLMSISE-00 atmosphere, to assess

- *The evolution of the magnitude of the drag force acting on the satellite, in conditions of active attitude control (FPM)*
- *The epoch corresponding to the earlier onset of a "peak" drag force along the orbit of 20 mN*
- *The epoch corresponding to the onset of an "average" drag force along the orbit of 20 mN*

Opening of the reentry window

Obtained by propagating the orbit corresponding to the earlier onset of a peak drag force of 20 mN (*27 October 2013, 09:06 UTC*), assuming the loss of attitude control and $C_D \times A$ = 11 m^2 (random tumbling spacecraft): *1 November 2013, 01:50 UTC*

Nominal reentry

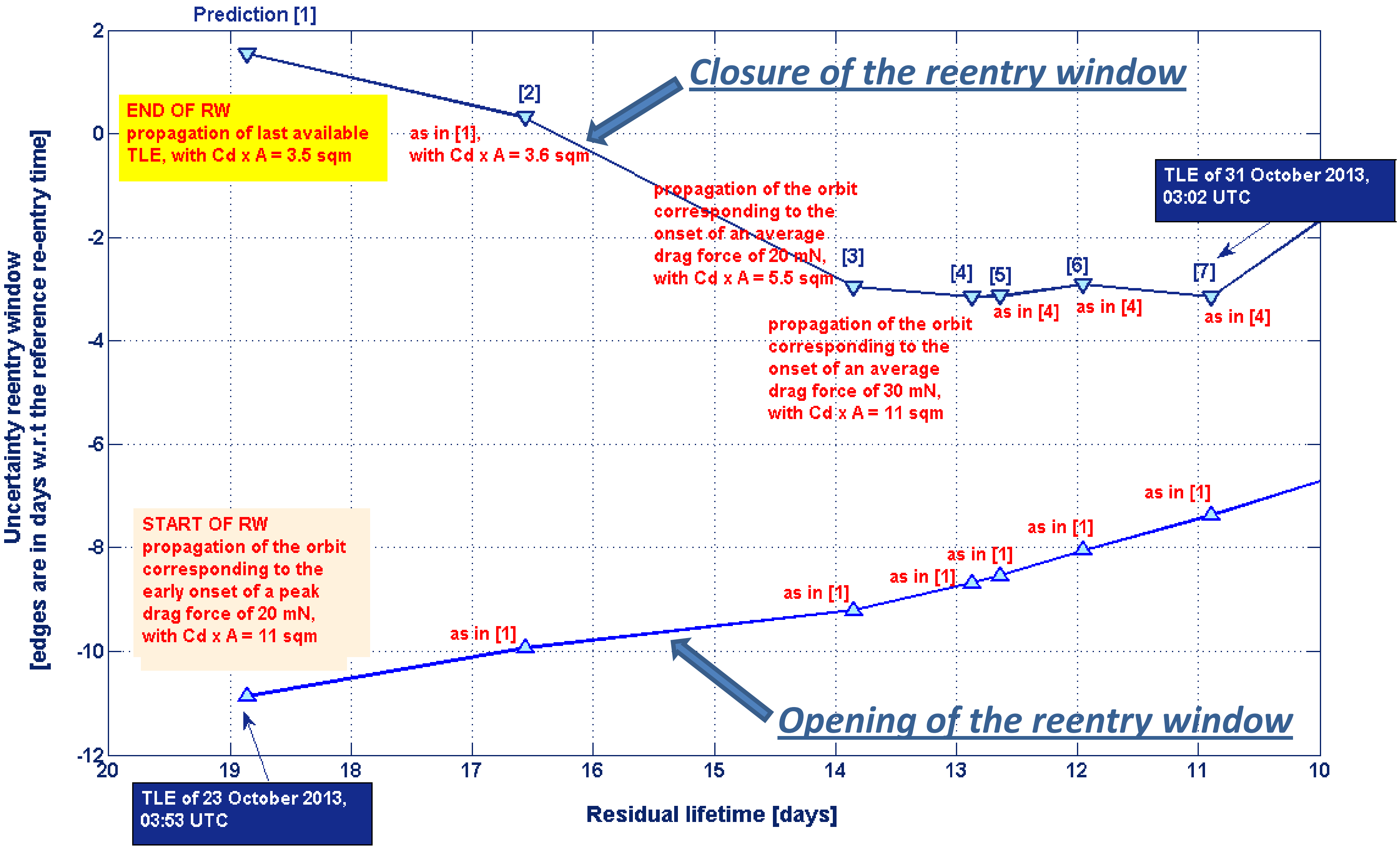
Predicted by propagating the orbit corresponding to the onset of an average drag force of 20 mN (*1 November 2013, 18:51 UTC*), assuming the loss of attitude control and $C_D \times A$ = 11 m^2 (random tumbling spacecraft): *4 November 2013, 22:06 UTC*

Closure of the reentry window

Obtained by propagating the last available two-line elements set with the estimated $C_D \times A$ = 3.60 m^2: *11 November 2013, 07:48 UTC* (FPM active until the end)

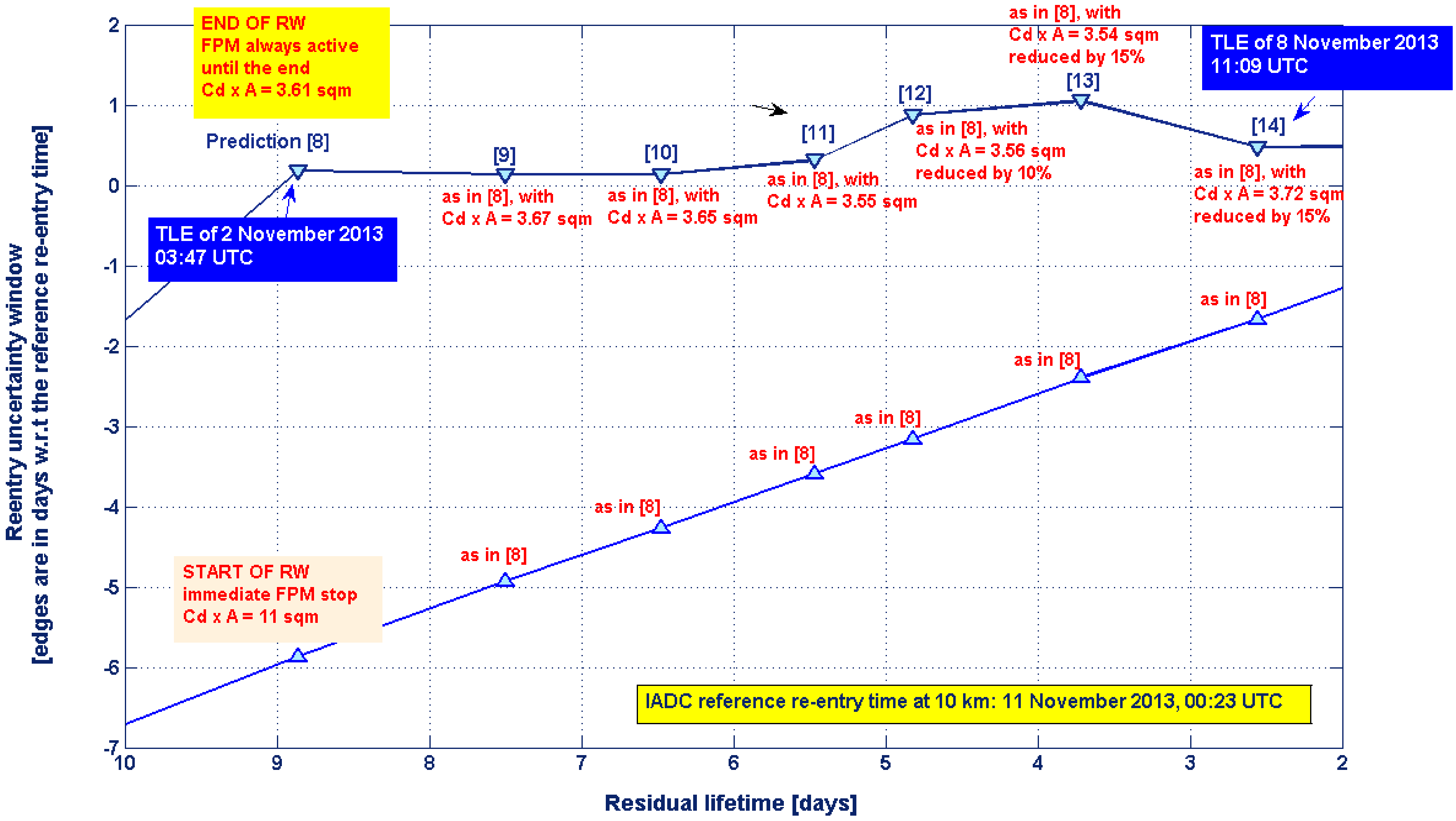
The definition was changed during the test phase

[23 – 31 October 2013]



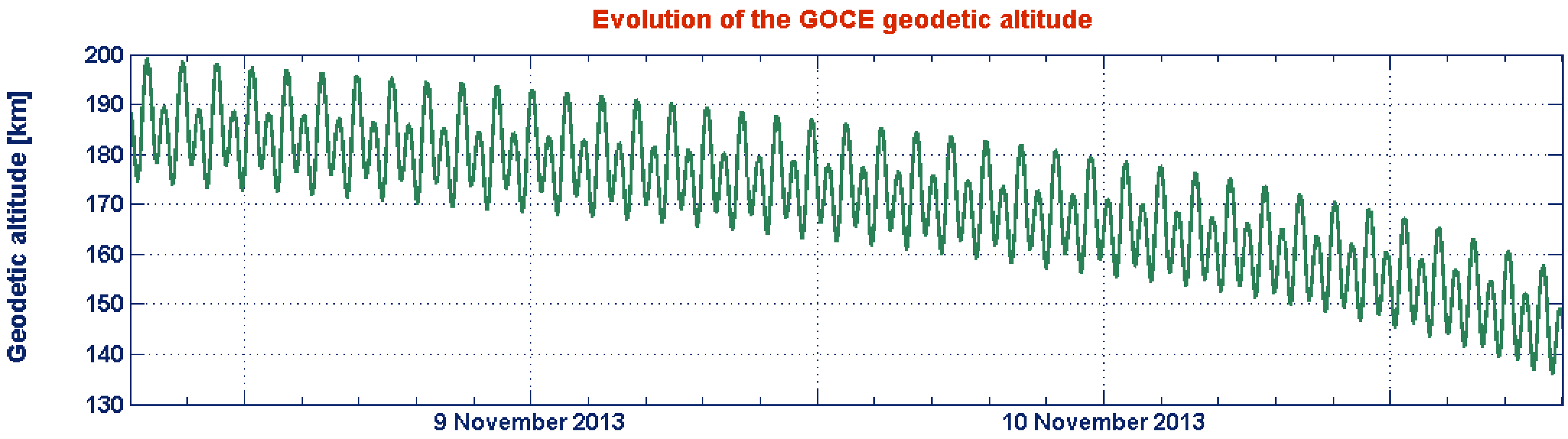
IADC reference reentry time at 10 km: 11 November 2013, 00:23 UTC

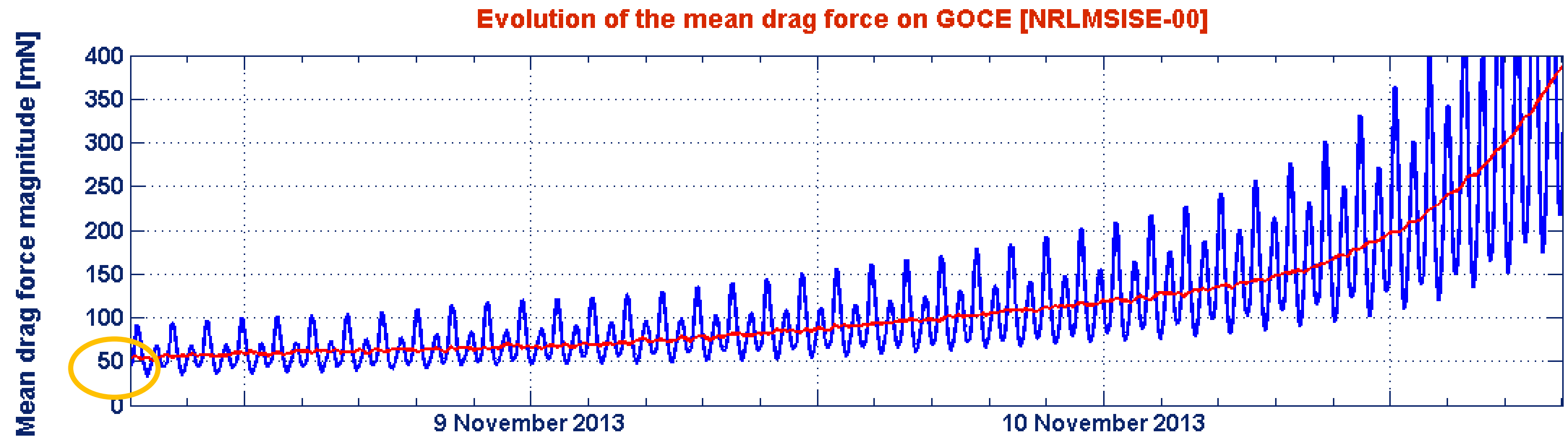
Operational definition of reentry uncertainty windows
[2- 8 November 2013]



Drag force evolution

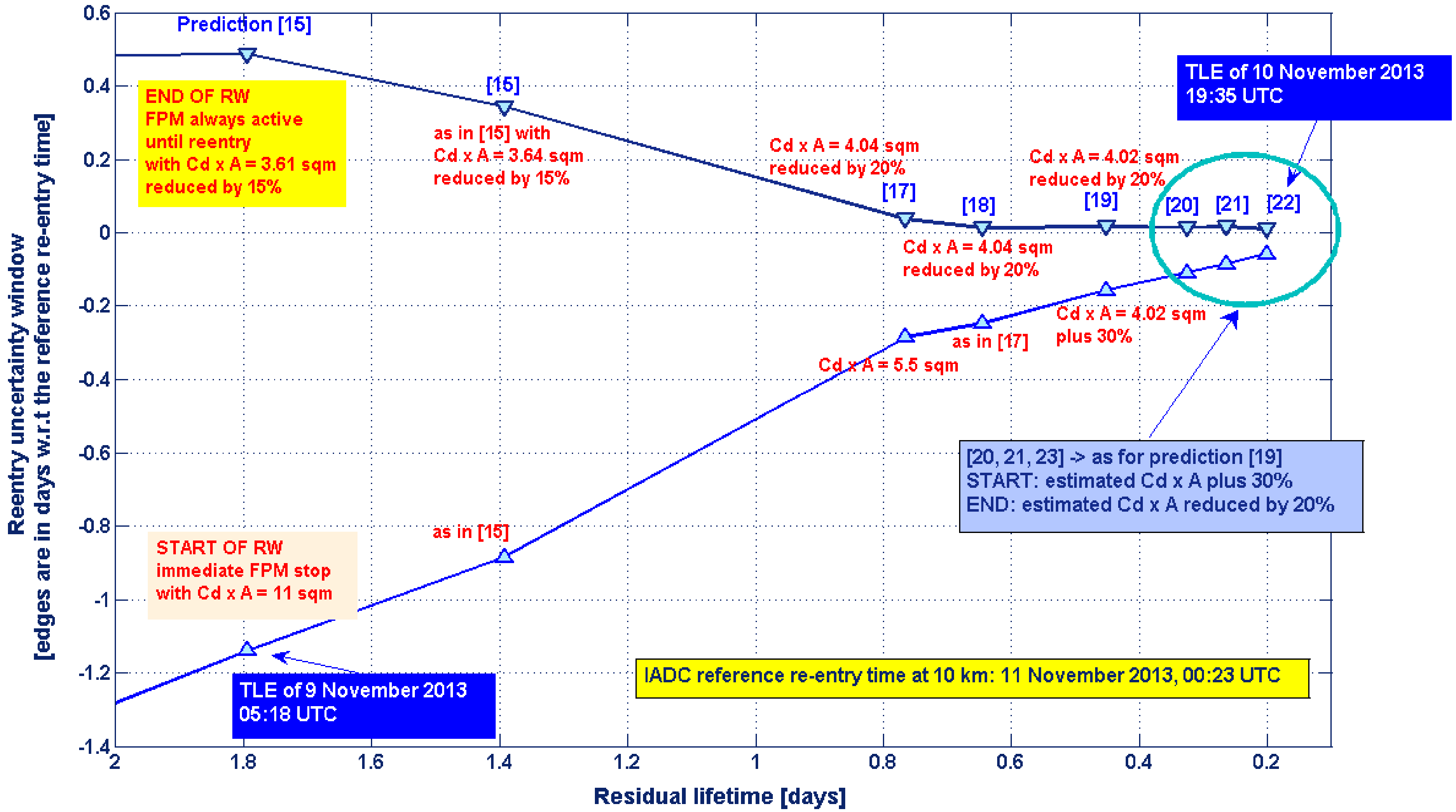
[issued on 8 November 2013]





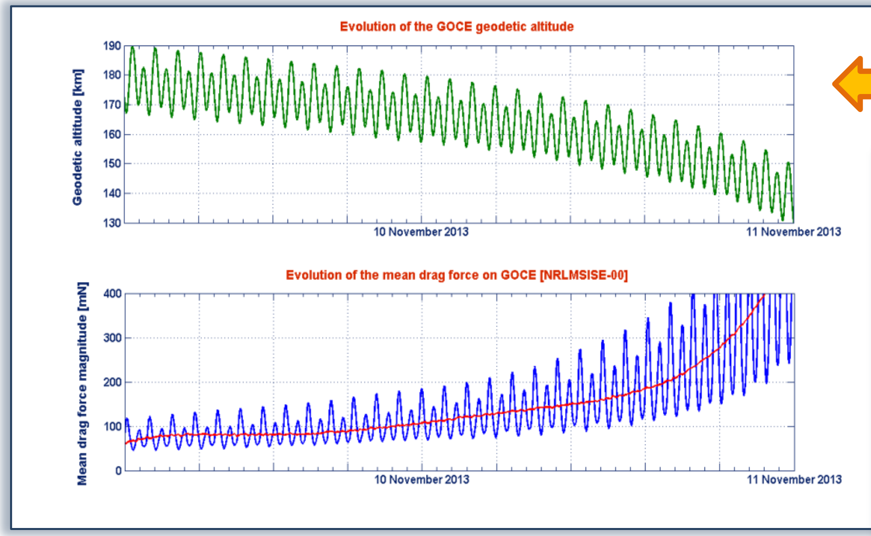
Final reentry uncertainty windows

[9 – 10 November 2013]

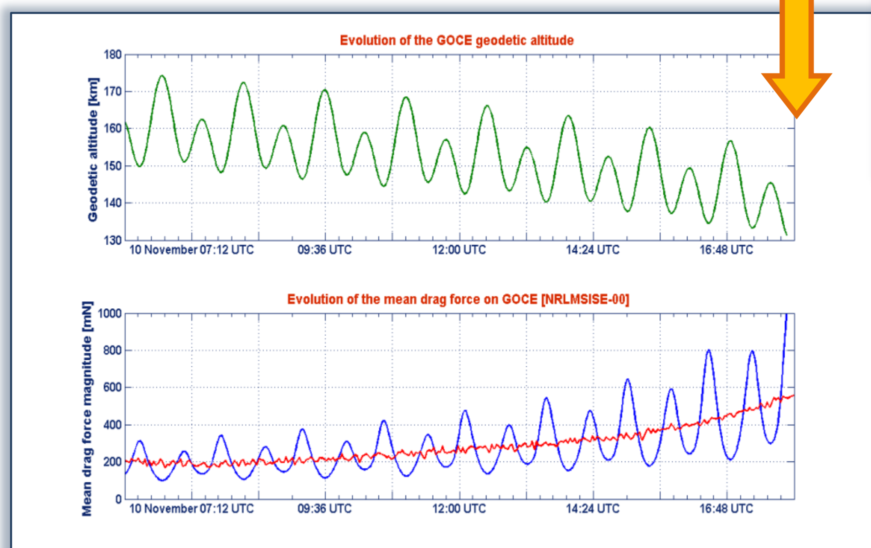


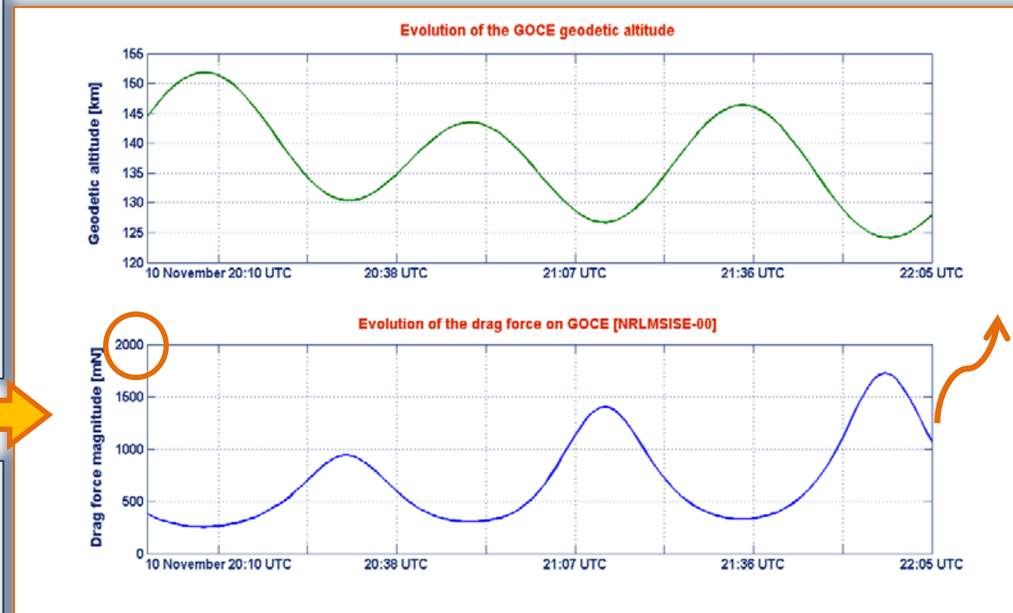
Drag force evolution
[issued on 9 & 10 November 2013]

9 November



10 November

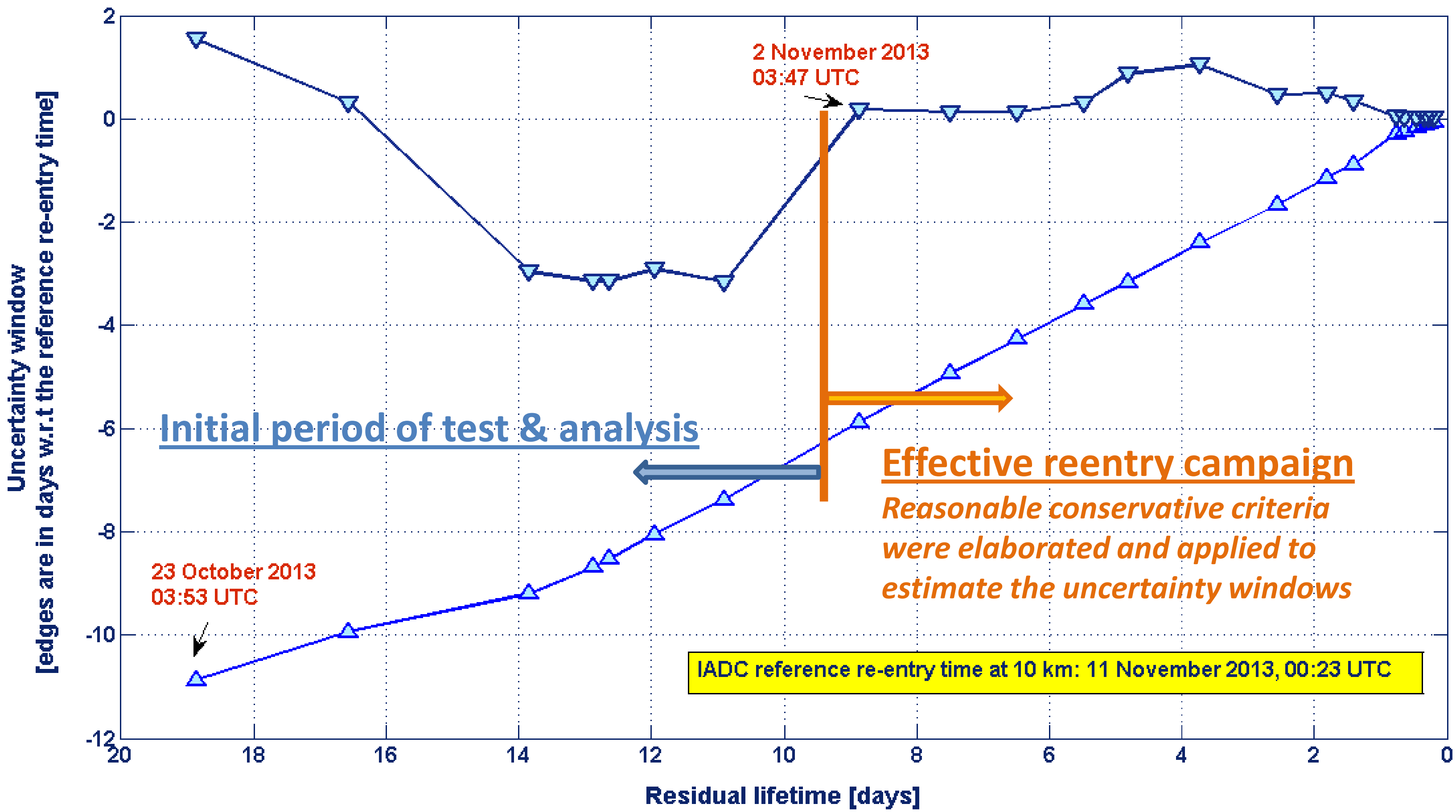




10 November 2013, 20:10 – 22:05 UTC

The system proved itself much more robust than envisaged, remaining operational until reentry, with drag forces probably exceeding 2000 mN

Reentry uncertainty windows



Estimated "nominal" reentry epoch at 10 km

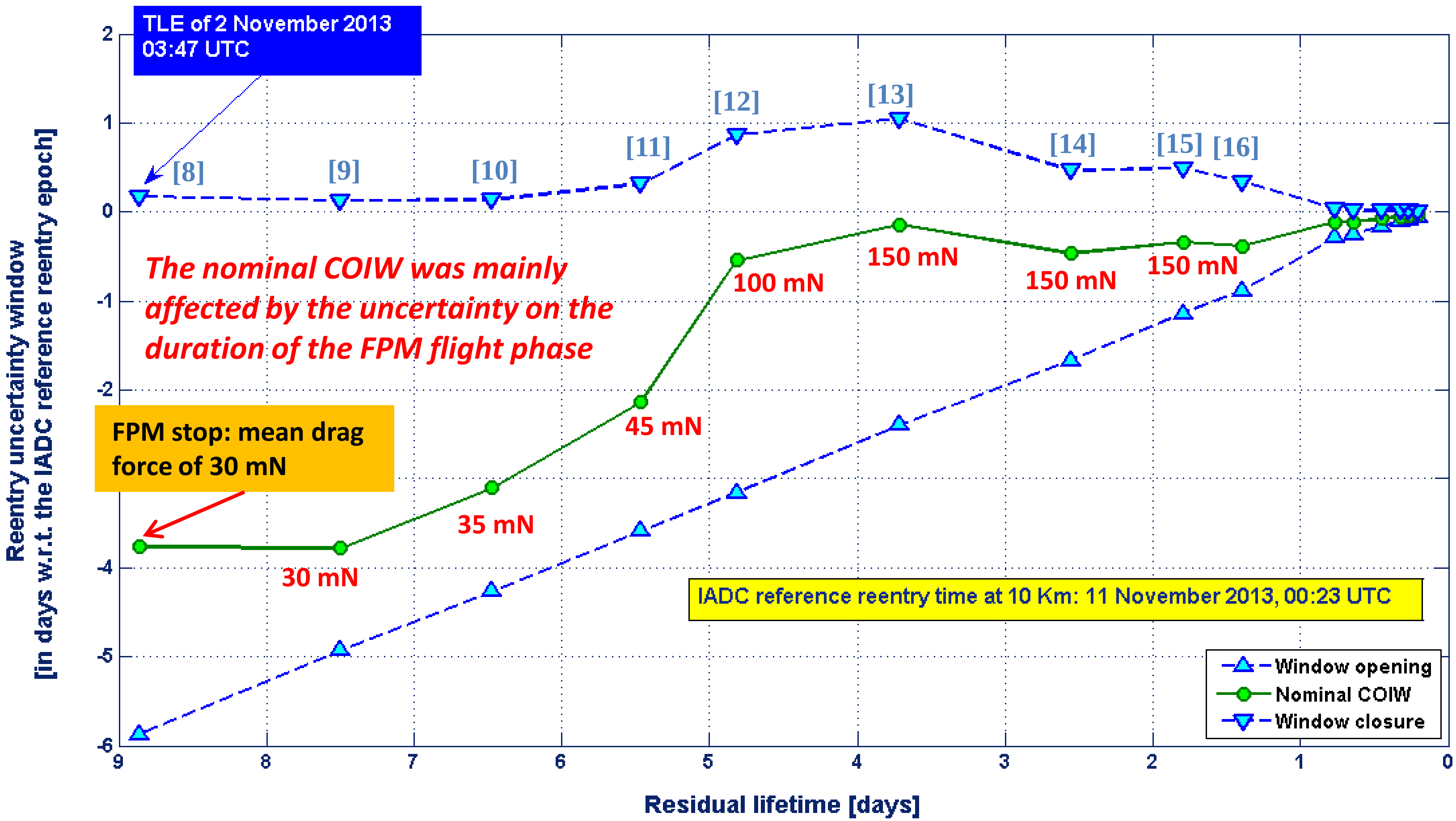
Due to the significant uncertainty surrounding the end of the FPM flight phase

Reentry predictions were highly speculative

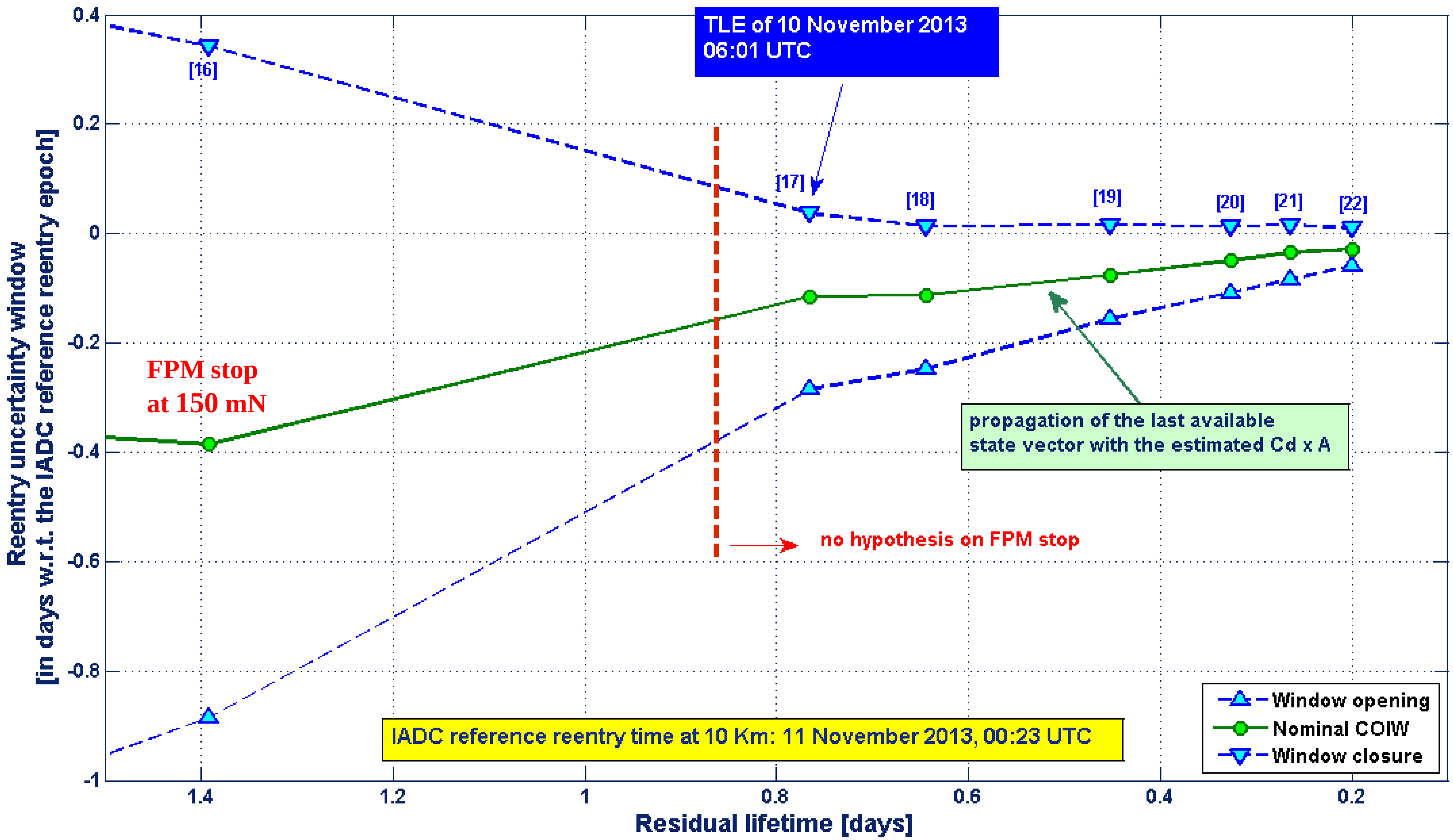
	Propagation of the orbit corresponding to the onset of an average drag force of	NOMINAL REENTRY EPOCH COIW yyyymmdd	hhmmss
1	20 mN	20131108	160300
2	20 mN	20131104	220545
3	20 mN	20131104	195916
4	20 mN	20131104	111107
5	20 mN	20131104	113500
6	20 mN	20131104	163859
7	20 mN	20131104	100457
8	30 mN	20131107	055450
9	30 mN	20131107	053417
10	35 mN	20131107	215016
11	45 mN	20131108	205643
12	100 mN	20131110	111614
13	150 mN	20131110	205330
14	150 mN	20131110	131013
15	150 mN	20131110	161547
16	150 mN	20131110	150708
	Propagation of the last available TLE, with the estimated Cd x A	yyyymmdd	hhmmss
17	4.04 m^2	20131110	213715
18	4.04 m^2	20131110	214056
19	4.02 m^2	20131110	223400
20	3.93 m^2	20131110	231300
21	3.76 m^2	20131110	233200
22	3.74 m^2	20131110	234300

Reentry predictions with uncertainties

[2 – 10 November 2013]



Reentry predictions with uncertainties
[9 – 10 November 2013]



Parametric evaluation of nominal reentry epochs at 10 km
[issued on 31 October 2013]

A detailed parametric analysis was carried out in order to explore the full set of possibilities, including also very low probability outcomes, according to the available information received from ESA

FPM stop	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

Estimated nominal reentry for FPM stop at 20 mN

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

Estimated nominal reentry for FPM active until the end

It is 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

Parametric evaluation of nominal reentry epochs at 10 km

FPM stop	Nominal Reentry
Immediate	7 Nov. 2013, 10:16 UTC
35 mN	8 Nov. 2013, 00:54 UTC
40 mN	8 Nov. 2013, 11:59 UTC
45 mN	8 Nov. 2013, 20:57 UTC
50 mN	9 Nov. 2013, 04:49 UTC
55 mN	9 Nov. 2013, 10:52 UTC
60 mN	9 Nov. 2013, 16:02 UTC
65 mN	9 Nov. 2013, 20:12 UTC
70 mN	9 Nov. 2013, 23:45 UTC
75 mN	10 Nov. 2013, 02:39 UTC
80 mN	10 Nov. 2013, 04:57 UTC
85 mN	10 Nov. 2013, 07:01 UTC
90 mN	10 Nov. 2013, 08:39 UTC
95 mN	10 Nov. 2013, 10:04 UTC
100 mN	10 Nov. 2013, 11:35 UTC
Always active	11 Nov. 2013, 07:57 UTC

[*issued on 5 November*]

FPM stop	Nominal Reentry
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*]

FPM stop	Nominal Reentry
Immediate	10 Nov. 2013, 03:09 UTC
100 mN	10 Nov. 2013, 05:40 UTC
150 mN	10 Nov. 2013, 15:07 UTC
200 mN	10 Nov. 2013, 18:26 UTC
300 mN	10 Nov. 2013, 21:55 UTC
Always active	11 Nov. 2013, 02:30 UTC

[*issued on 9 November - 2°*]

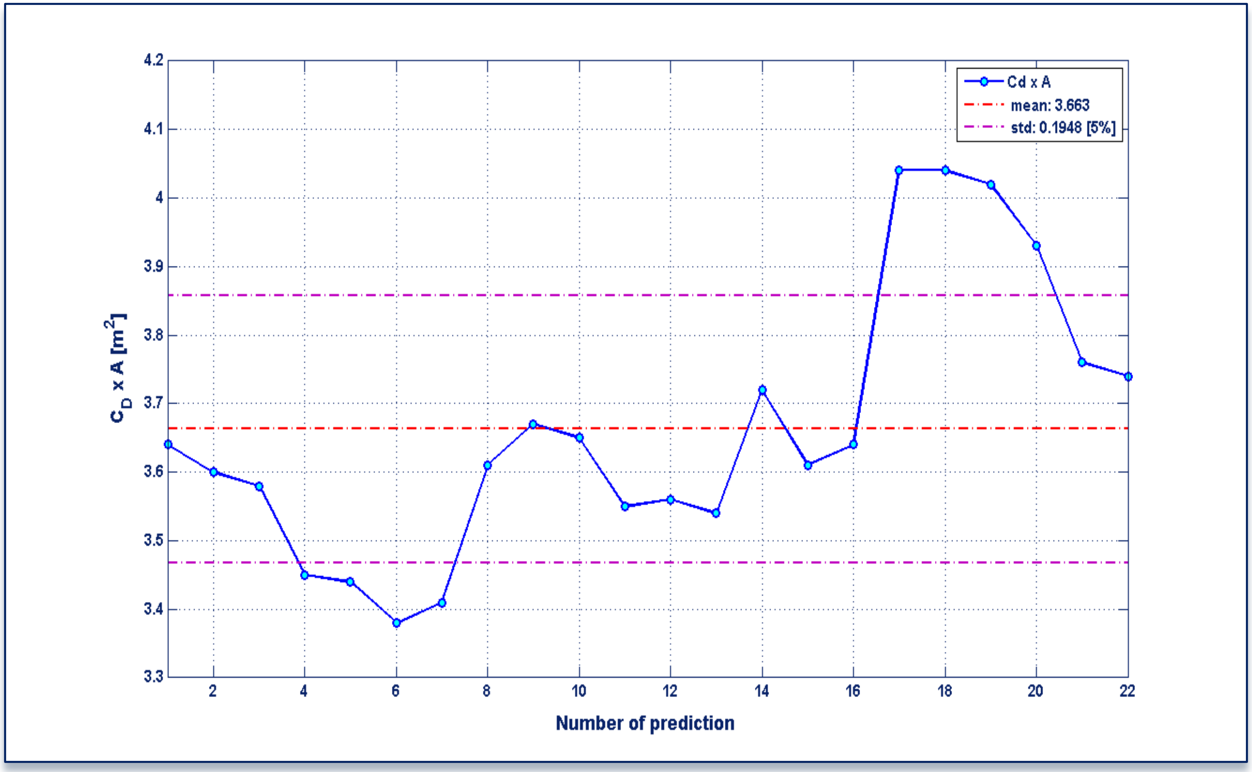
Estimated evolution of $C_D \times A$
[NRLMSISE-00 density model]

Pred.	Retro-fit over the last # TLEs	C_D x A [m²]
1	6 US	3.64
2	12 US	3.60
3	20 US	3.58
4	24 US	3.45
5	14 ESA	3.44
6	28 US	3.38
7	32 US	3.41
8	28 US + ESA + Russian	3.61
9	31 US + ESA + Russian	3.67
10	44 US + ESA + Russian	3.65
11	48 US + ESA + Russian	3.55
12	72 US + ESA + Russian	3.56
13	63 US + ESA + Russian	3.54
14	14 US	3.72
15	22 Russian	3.61
16	23 US	3.64
17	11 Russian	4.04
18	20 US + ESA + Russian	4.04
19	22 US + ESA + Russian	4.02
20	28 US + ESA + Russian	3.93
21	8 ESA	3.76
22	9 ESA	3.74

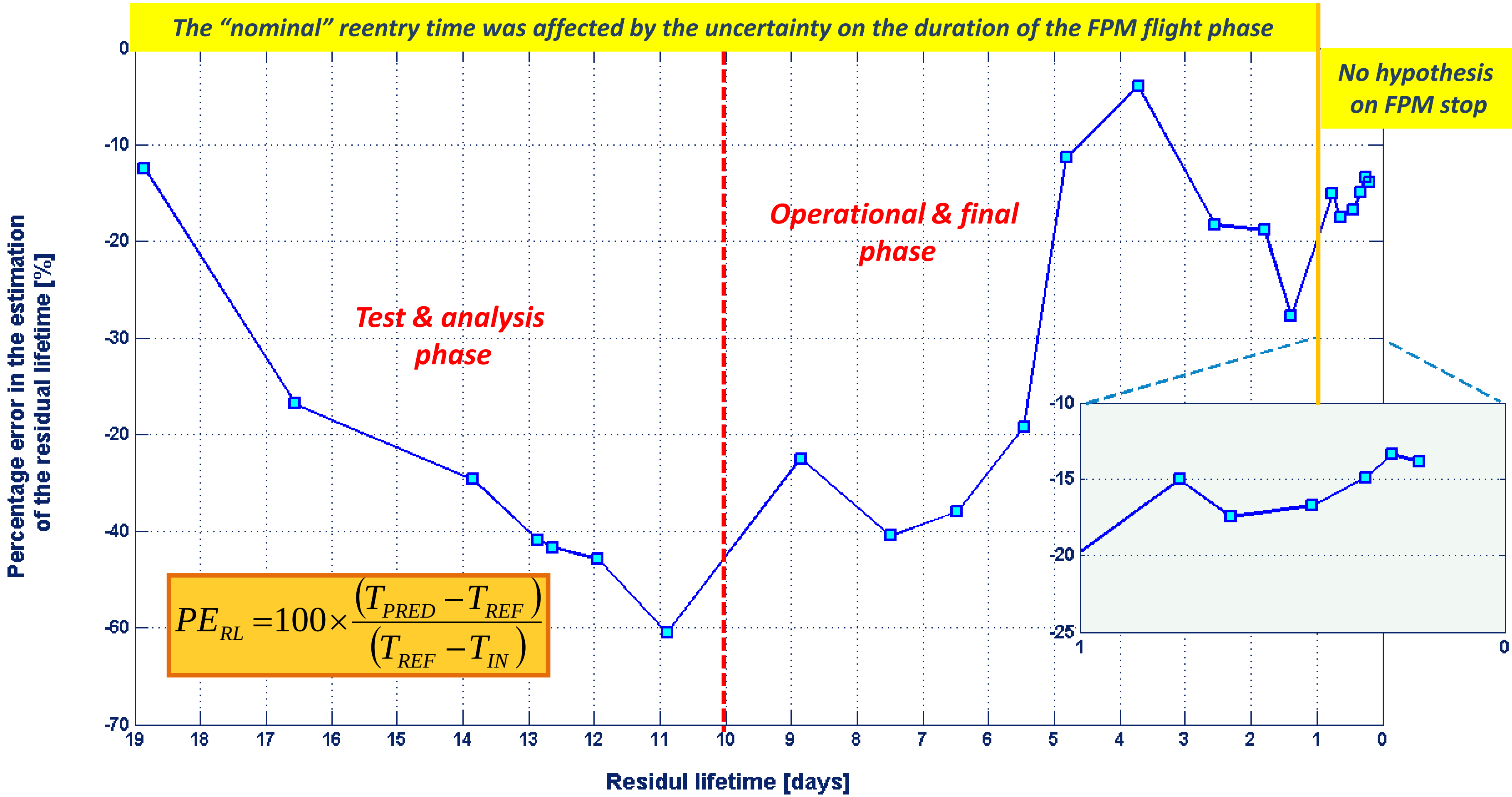
C_D x A in FPM mode [ESA specifications] $C_{D\text{-}FPM} = 3.5$ m²

Mean estimated C_D x A $C_{D\text{-}ME} = 3.663$ m²

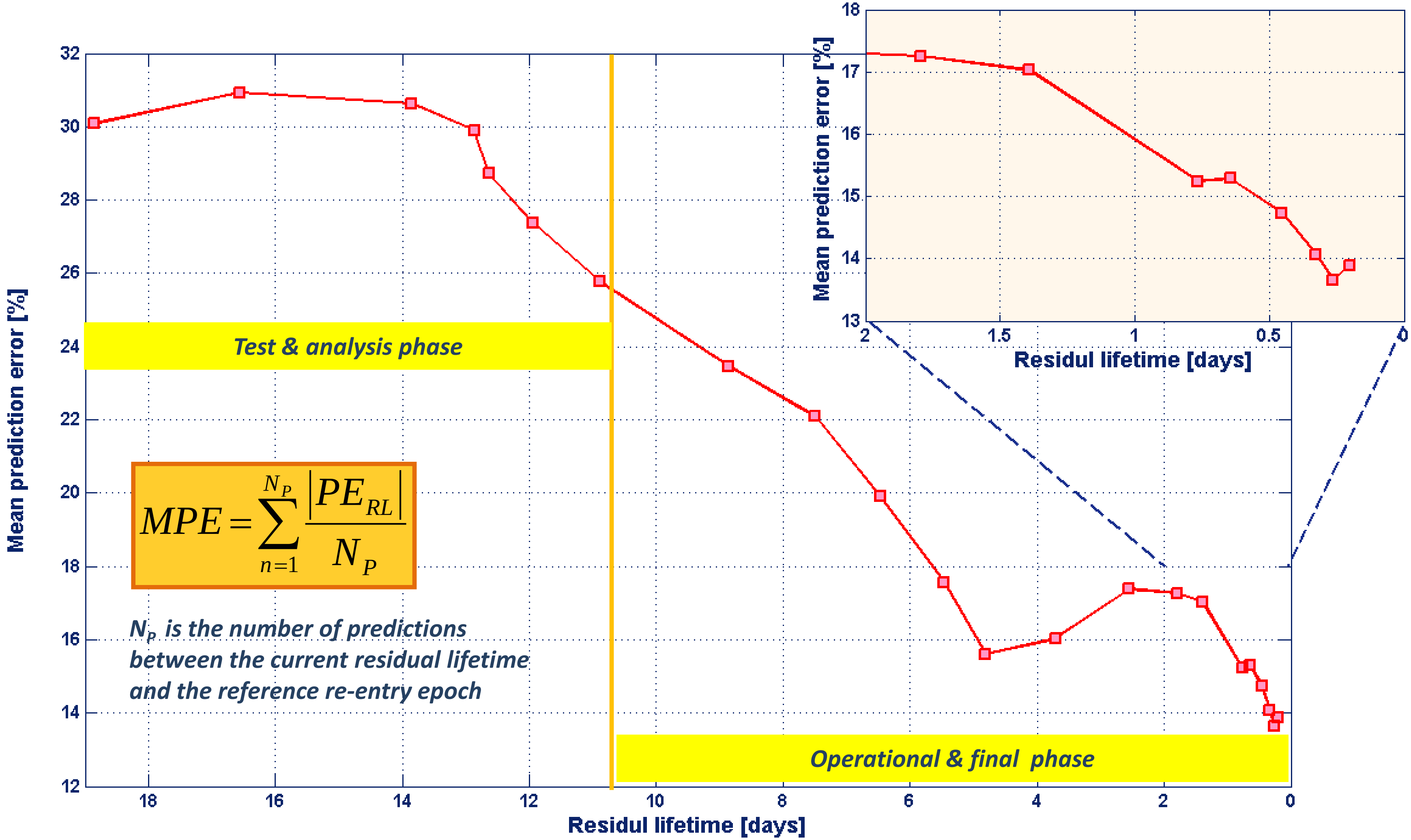
$100 \times (C_{D\text{-}ME} - C_{D\text{-}FPM}) / C_{D\text{-}FPM} \sim 4.7$ (< 5%)



Percentage error in the estimation of the residual lifetime



Mean prediction error affecting the estimation of the "nominal" reentry epoch at 10 km



$$MPE = \sum_{n=1}^{N_P} \frac{|PE_{RL}|}{N_P}$$

N_P is the number of predictions between the current residual lifetime and the reference re-entry epoch

For each sub-satellite location included in the global reentry window

In each place the eventual impact may occur only during a specific <u>risk time window</u>, which can be therefore used to plan risk mitigation measures on the ground and in the overhead airspace

Definition of the risk time windows for Italy associated with the GOCE reentry

- *The reentry predictions issued by IADC conventionally assume that no fragmentation occurs during reentry, and the nominal reentry time considered is that corresponding to the simulated descent of the intact satellite at the geodetic altitude of 10 km*

- **The boundaries of the risk time windows valid for the Italian territory and airspace, *i.e. from the geodetic altitude of 12 km down to ground impact*, were determined**

  - **by subtracting 10 minutes (lower bound)**
  - **and by adding 30 minutes (upper bound)**

  to the simulated ground impacts on Italy, included in the global uncertainty window and computed with SATRAP for the reference IADC object, i.e. the intact satellite

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 the aircraft in flight**

Possible reentry opportunities over Italy

For a given global reentry uncertainty window, where and when a reentering fragment would have crossed the national airspace and hit the ground?

- Starting 2-3 days before the satellite plunge into the atmosphere, all possible reentries over Italy, included in the current uncertainty window, were simulated
- In practice, the nominal predicted trajectory was slightly modified, through small changes of the ballistic parameter, in order to simulate the reentry over Italy. The time corresponding to the nominal ground impact was then adjusted to account for the GOCE fragmentation, according to the definition of the risk time windows for Italy
- The associated ground tracks crossing Italy were computed with the "right" times and roughly included the reentry dynamics up to ground impact; the uncertainty swaths reflected the cross-track trajectory inaccuracies and debris dispersion

There were 6 possible reentry opportunities over Italy 61 hours before reentry

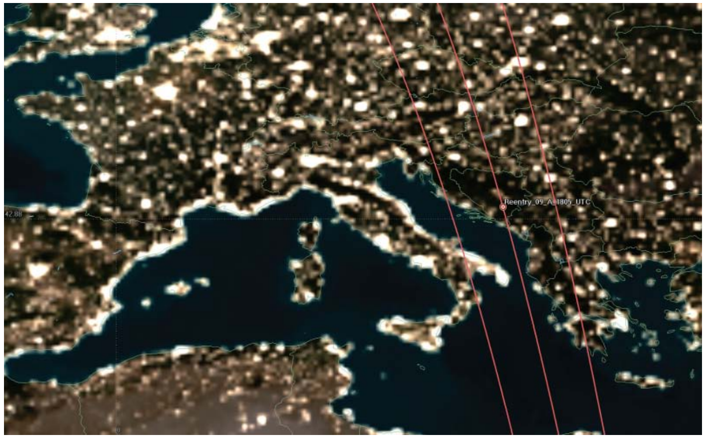
The global uncertainty window included
6 possible reentry opportunities over Italy
on 8 November 2013, 11:30 UTC

1.	9	November	(descending)	Opening: 06:37 UTC	Closure: 07:17 UTC
2.	9	November	(ascending)	Opening: 17:55 UTC	Closure: 18:35 UTC
3.	10	November	(descending)	Opening: 07:26 UTC	Closure: 08:06 UTC
4.	10	November	(ascending)	Opening: 18:44 UTC	Closure: 19:24 UTC
5.	11	November	(descending)	Opening: 06:48 UTC	Closure: 07:28 UTC
6.	11	November	(ascending)	Opening: 18:10 UTC	Closure: 18:50 UTC

- *4 at minus 56 hours (2, 3, 4, 5)*
- *3 at minus 40 hours (3, 4, 5)*
- *2 at minus 25 hours (4, 5)*
- ***Only 14 hours before reentry it was possible to exclude any residual risk of debris fall on the Italian territory***

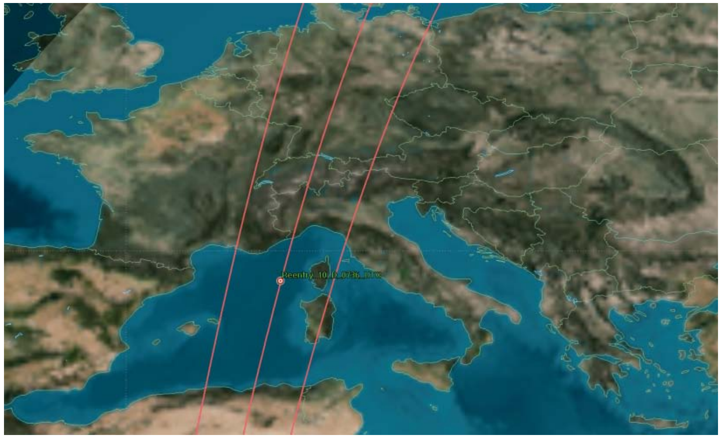
Possible reentry ground tracks over Italy

After the identification of the few potentially critical reentry tracks and of the corresponding risk time windows for Italy, the tracks left outside the progressively shrinking global uncertainty window were eliminated, focusing the attention on what remained

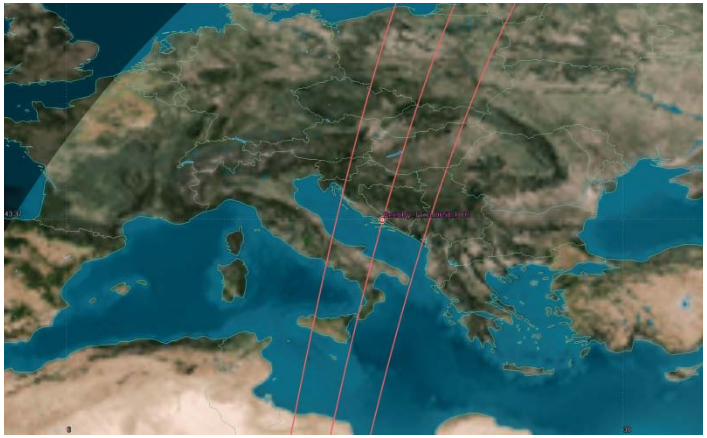


Track 2. 9 November, Opening: 17:55 UTC; Closure: 18:35 UTC

Track 4. 10 November, Opening: 18:44 UTC; Closure: 19:24 UTC



Track 3. 10 November, Opening: 07:26 UTC; Closure: 08:06 UTC

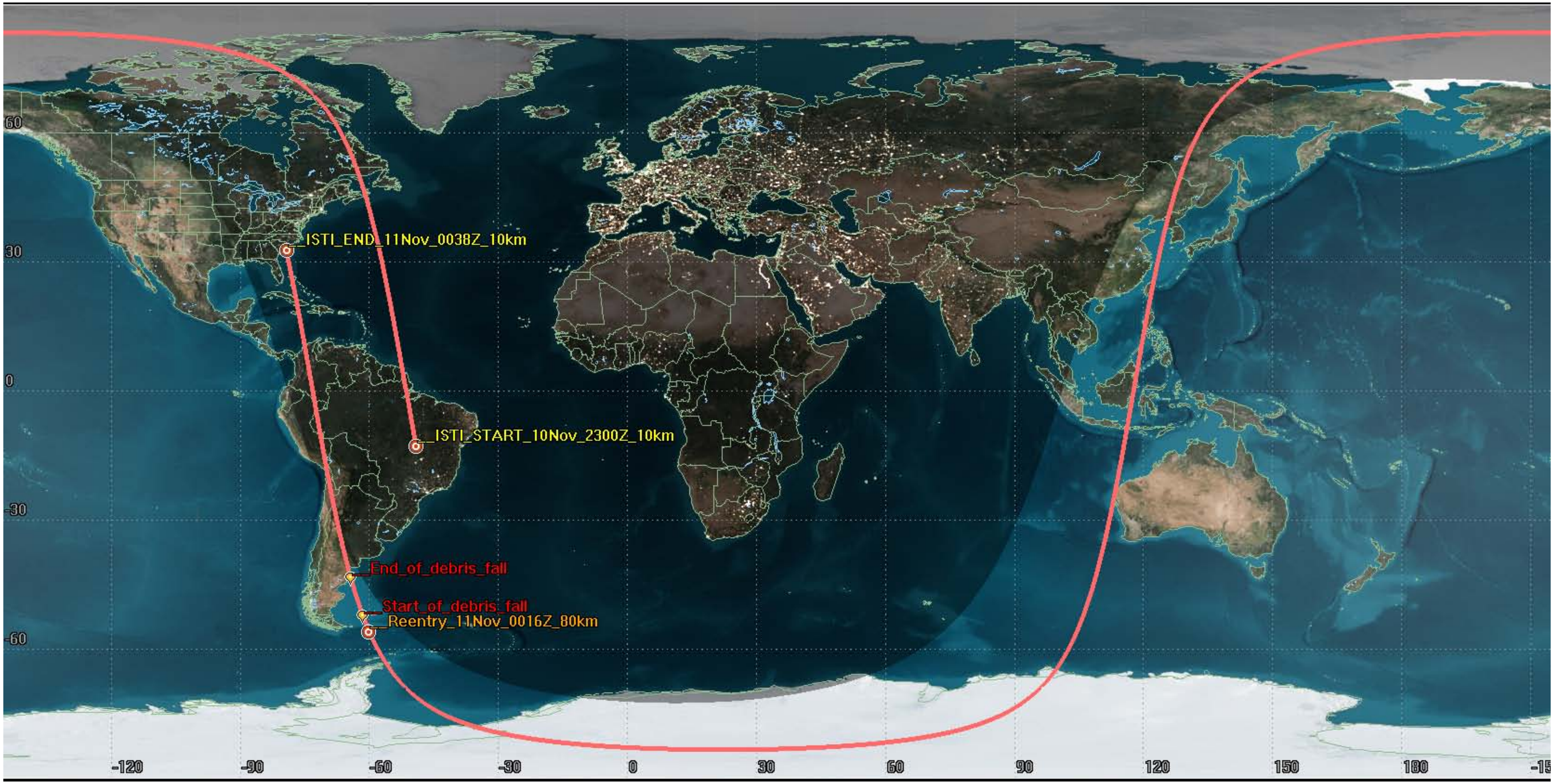


Track 5. 11 November, Opening: 06:48 UTC; Closure: 07:28 UTC

Global reentry uncertainty window
[Prediction N. 22 – TLE: 10 November 2013, 19:35 UTC]

Final global ground track associated with the last reentry prediction uncertainty issued by ISTI/CNR to IADC approximately 4 hours before reentry

The GOCE fragments 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 (in red)



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

ACKNOWLEDGMENTS

- **IADC Re-Entry Database hosted at ESA/ESOC and US Space Track Organization for the GOCE orbital elements**
- **NOAA/NGDC and Jan Alvestad for the daily observed values of the solar and geomagnetic indices**
- **NOAA/SEC and British Geological Survey for the predicted values of the solar and geomagnetic indices**
- **Figures were generated either with MATLAB R2012a or through the AGI's Satellite Tool Kit (STK), Version 8.1.0**

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