Radar-based Re-Entry Predictions with very limited tracking capabilities: the GOCE case study

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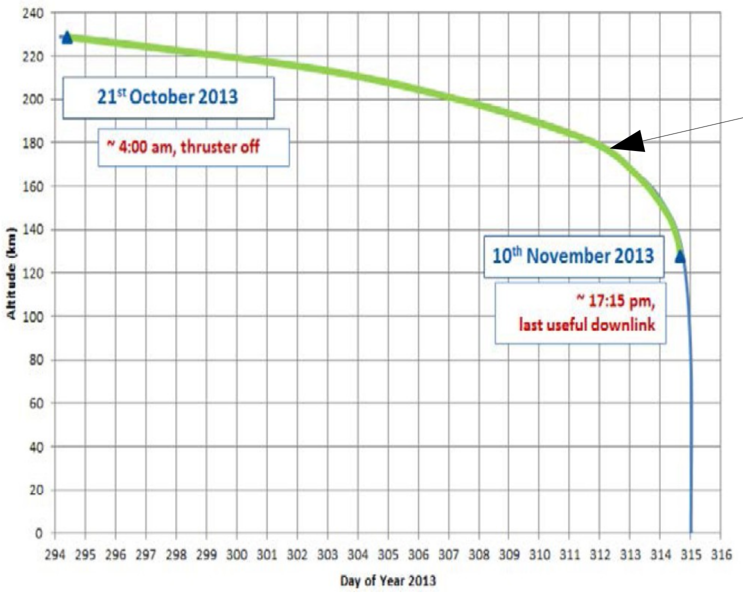
4th International Workshop on Space Debris Re-entry
ESOC Feb/28 – Mar/01 2018

Introduction

During the entire ***GOCE mission***, up to the final orbits before re-entry, the spacecraft was working nominally and provided its position via **GPS measurement** downlinked as telemetry.

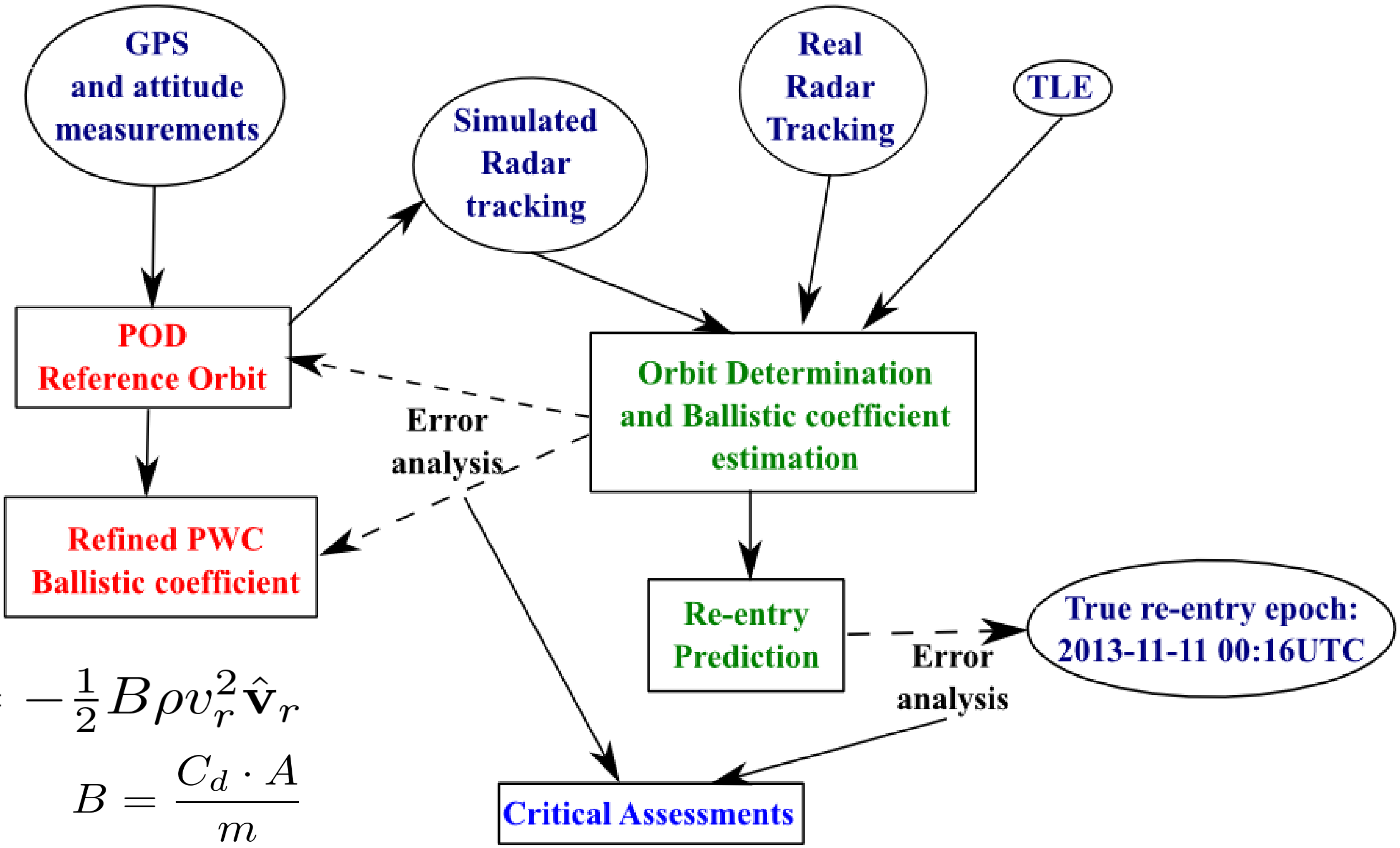


Continuous GPS and attitude data

Many other sensors have followed GOCE as well, e.g. **FHR TIRA Radar**, within the IADC's 2013 re-entry campaign.

The main goal of this study is to assess the dependency of **re-entry predictions uncertainties** on the **quality of the orbit determination** and observation frequency.

Main Strategy



$$a_{drag} = -\frac{1}{2} B \rho v_r^2 \hat{\mathbf{v}}_r$$

$$B = \frac{C_d \cdot A}{m}$$

This work has been carried out within the ESA *EXPRO+"Benchmarking Re-Entry Prediction Uncertainties"* project.

Previous work

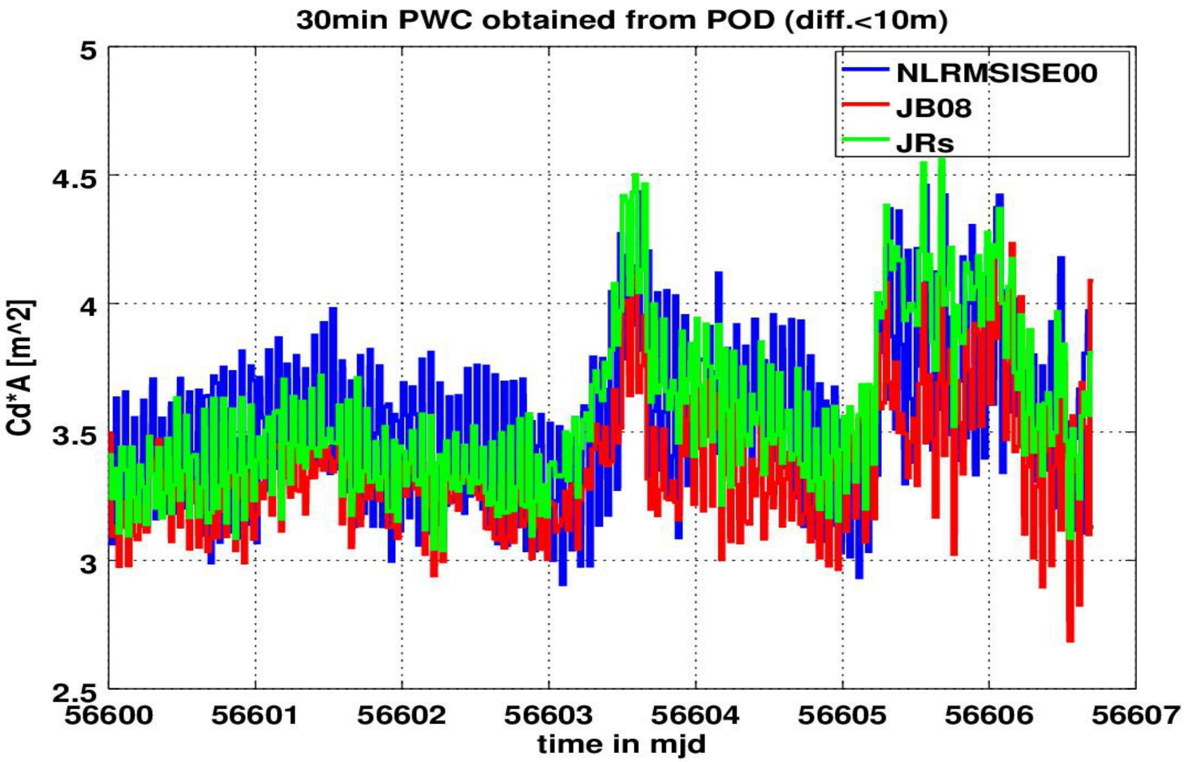
In previous works, **Lemmens et al.2014**, **Cicalò et al.2017**, the main focus was on the german **TIRA radar** and on **similar tracking sensors** (*Poster Pres. 7th European Conference on Space Debris, April 2017*):

- **Under reasonable conditions**, radar-based OD is very effective in estimating the **average evolution** of the ballistic coefficient, in comparison to the one estimated from GPS-POD, even from a single site.

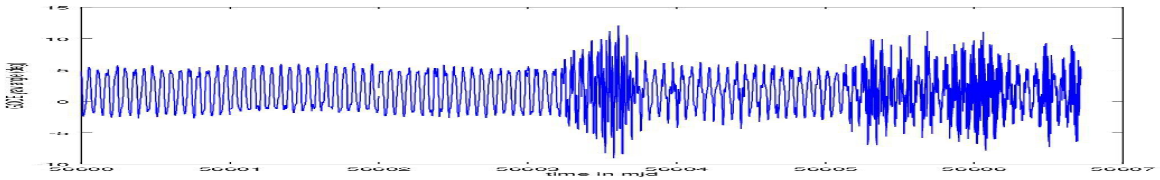
- POD hides the **instrinsic** large errors in the dynamical models, by fitting empirical accelerations, which re-appear in the radar-based OD as large observations residuals.

- Guaranteeing observational sessions up to **few hours before re-entry** is always recommended to reduce the size of re-entry windows, this **cannot be guaranteed with a single station**.

30min-PWC coefficient estimated from POD



Yaw angle



There is a correlation with the GOCE yaw angle, we can distinguish the peaks at day 18 and days 20-21.

Recent work

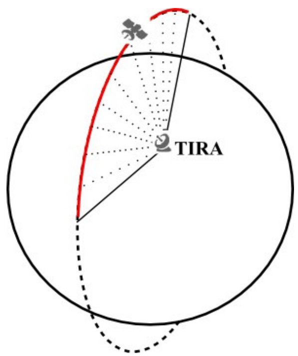
More recently, additional analysis has been carried out on the Northern European sensor **EISCAT UHF** radar, located in Tromsø, Norway.

- This sensor, originally conceived for atmospheric studies of the ionosphere, has been recently considered for space debris applications, in particular for **tracking of specific targets**, and to **support re-entry predictions**.

- Its very **limited tracking capability** poses the problem of establishing to which extent it can be useful to support OD and re-entry predictions, in comparison to TIRA-like standard performances.

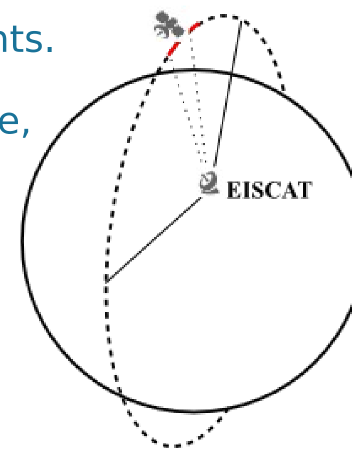
TIRA and EISCAT UHF main assumptions

	TIRA	EISCAT
Location	~50.62°N 7.13°E 340.32m	~69.58°N 19.23°E 85.55m
Assum. Obs. noise	r~10m, Az/El~0.01°	r~15m, rr~1m/s
Min El. Thr.	~3°	~30°



Note for EISCAT[1]: The antenna controller cannot smoothly track targets, it can only move to a position, stop there, and wait for the object to pass through the beam
→ limited tracking observations of targets (**few seconds of data**) with approximately known orbital elements.

Scheduler: ~1 short track per minute, per pass.



Example of tracks:

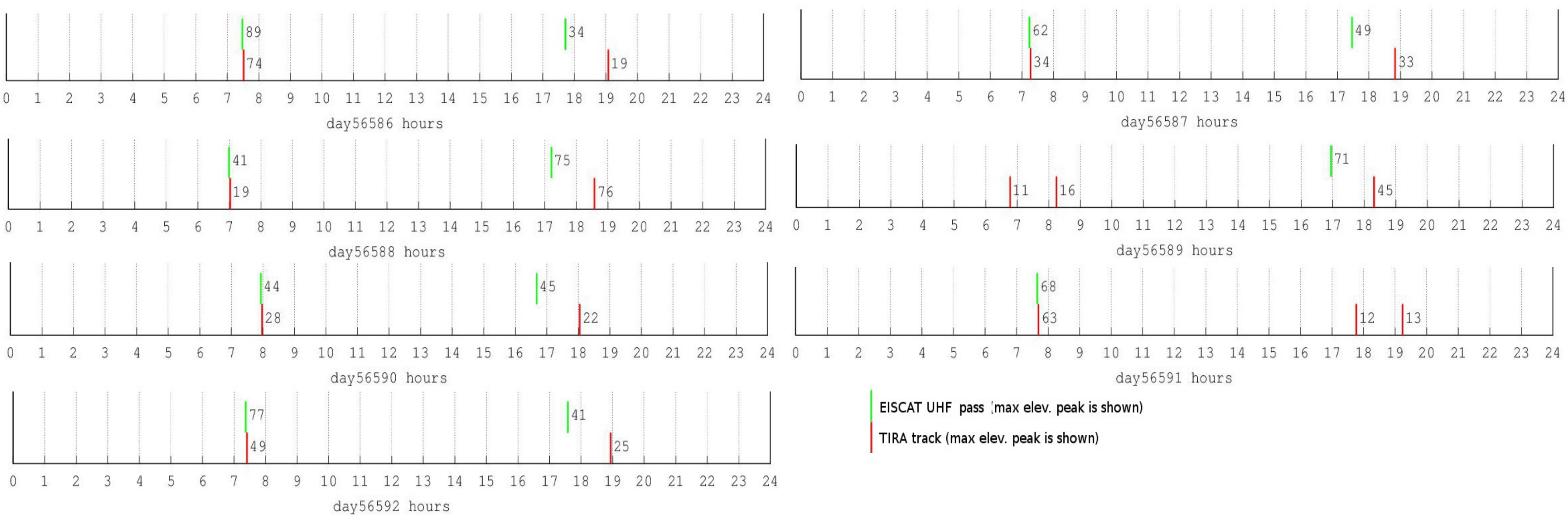
Station	Target	Data start	Data end	
TIRA	GOCE	2013-10-22 07:17:06 UTC	2013-10-22 07:22:28 UTC	Max El. ~34°
EISCAT	2012-006K	2016-10-21 16:19:48.98 UTC	2016-10-21 16:19:50.38 UTC	Az/El ~165°/66.5°

[1] Vierinen J., *SSA P2-SST-II SST-Radar Observation* Executive Summary 2017.

Simulation of radar observations

- The GOCE POD is used as reference trajectory to generate realistic radar tracks, from TIRA and EISCAT UHF, for the 3 weeks of decay (from MJD-56586 to MJD-56606).
- The average duration of visibility over the station is **~5min** for TIRA and **~1min** for EISCAT.
- This implies just **one scheduled track of few seconds from EISCAT** per pass.

Example of visibility from TIRA (with max El. >10°) and EISCAT during the first week of decay (2013 Oct/21–Oct/27):



OD errors

Re-entry prediction scenario: simply a selection of tracks to be used for OD and estimation of ballistic parameter ($\mathbf{x}_0$,$\mathbf{v}_0$,B), to propagate until re-entry time (e.g. h~90km).

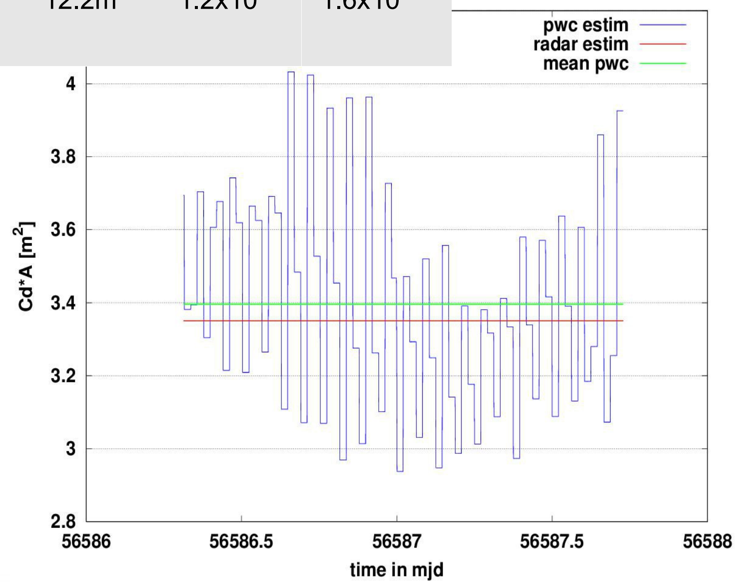
Example. Two comparable radar-based scenarios: **first 4 TIRA tracks** vs **first 4 EISCAT tracks** (same total obs. time span ≅ first 36h days of GOCE decay).

Comparison with POD reference orbit over the total obs. time span:

RMS of diff. over total obs. time span	Δ**x**-R	Δ**x**-T	Δ**x**-W	Δ**v**-R	Δ**v**-T	Δ**v**-W	Δa	Δe	Δ(ω+M)
TIRA-based sol. vs POD	192.0m	542.7m	81.7m	0.5m/s	0.2m/s	0.1m/s	10.3m	3.4×10^{-5}	3.2×10^{-3} °
EISCAT-based sol. vs POD	797.1m	2620.9m	808.6m	2.6m/s	0.9m/s	0.9m/s	12.2m	1.2×10^{-4}	1.6×10^{-2} °

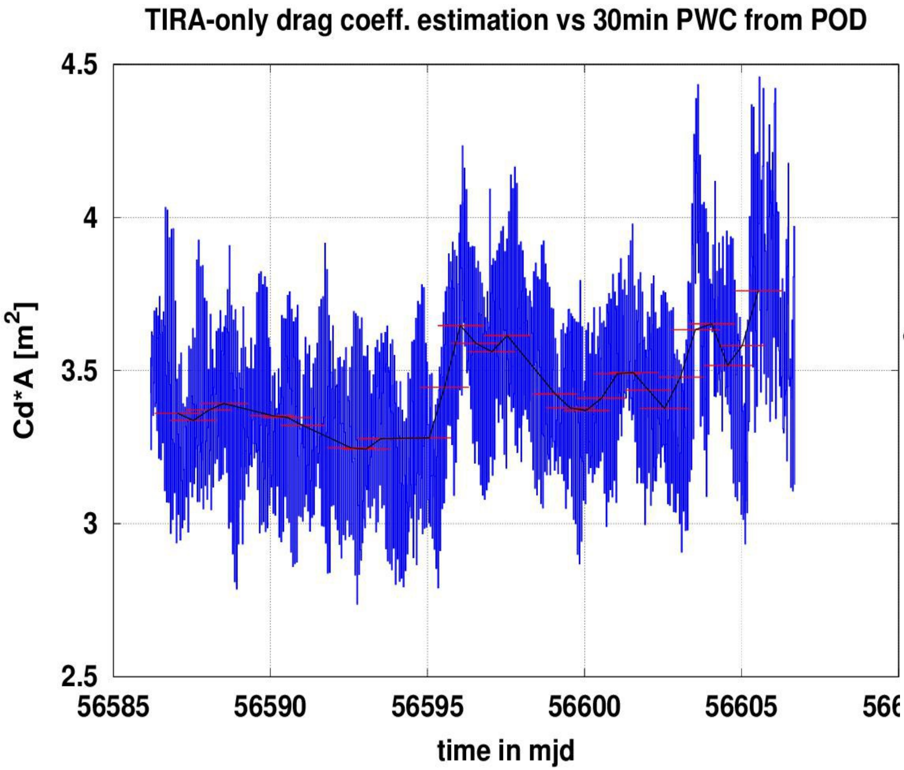
Estimated ballistic coefficients are close to the mean value of PWC coefficient to **1%** level in both cases.

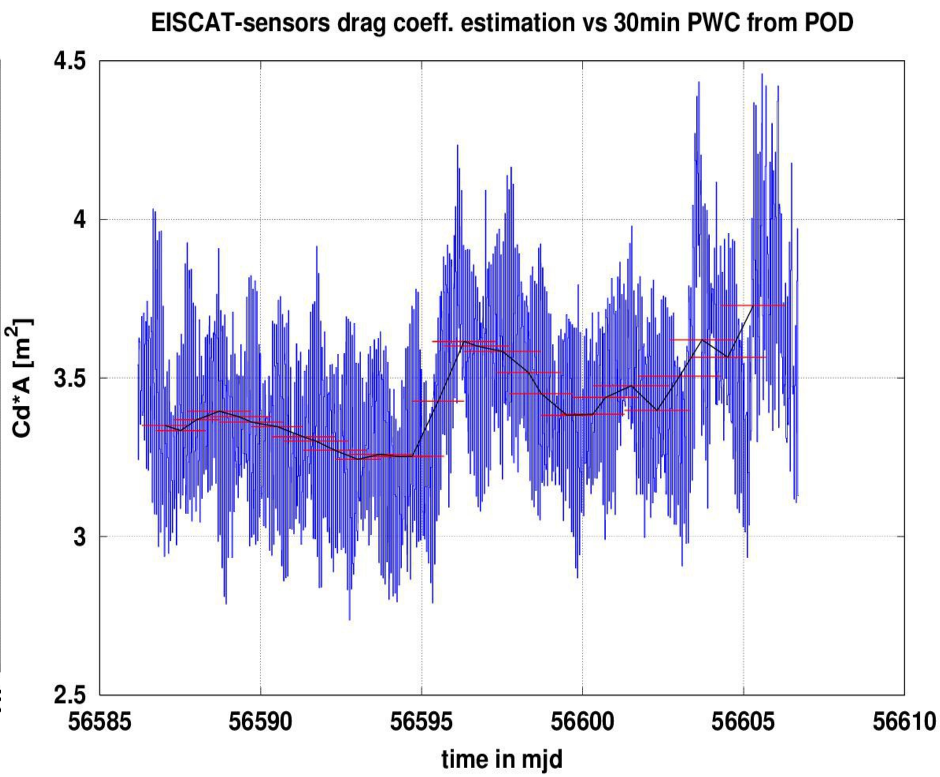
Re-entry predictions are Nov-11 ~11:24 UTC and Nov-11 ~12:46 UTC, thus **very much aligned** (from ~20 days before re-entry).



TIRA and EISCAT-based calibrations

GOCE **TIRA-based** (Left) and **EISCAT-based** (Right) drag coefficient calibrations over time intervals of ~36h (in red), compared with **POD-based** 30min PWC coefficient (in blue).

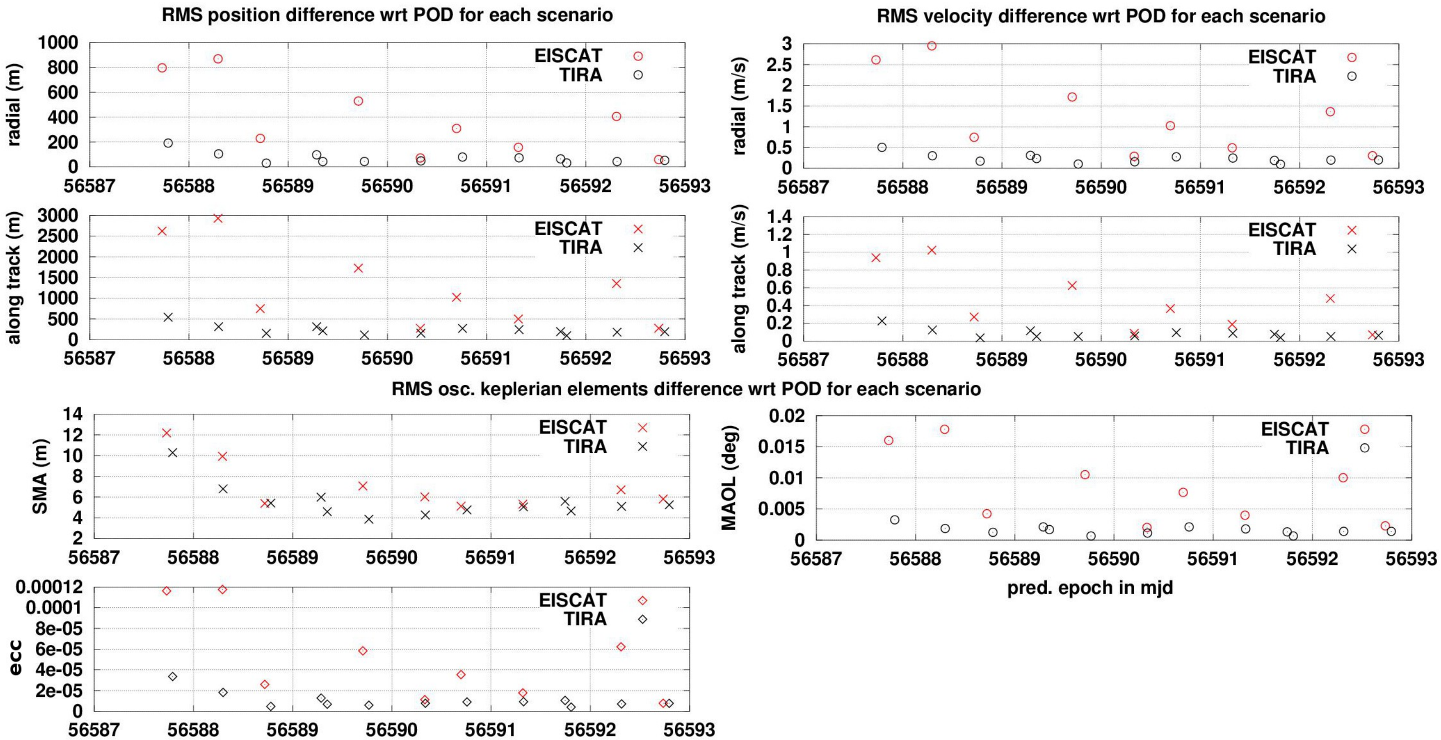




The ballistic coefficient relative difference (in percentual) w.r.t. the mean of the 30min PWC coefficient over each observation time span is **below 2%**.

OD errors and variation of re-entry time

- In terms of **estimation of the re-entry epoch**, the EISCAT-only simulated campaign turns out to be **equivalent** to the TIRA-only one over comparable observation time spans.
- In terms of the **overall OD accuracy**, the TIRA-based solutions are better, due to the larger availability of good measurements.



- **Correlations** between position and velocity errors are large (>0.99), correlations between *a*, *e* and ω+*M* errors are generally low (<0.5).

OD errors and variation of re-entry time

We set up a **simplified computation** to give us a quantification of the variation of the computed re-entry time in function of the initial conditions errors, in Keplerian elements.

Epoch of prediction fixed on Oct-25, the initial conditions are varied inside an interval.
With the nominal initial conditions and a CdA=3.4m^2, the nominal re-entry is on Nov-11 at 7:49:48UTC.
For each new initial condition a re-entry time is computed, and the variations evaluated.

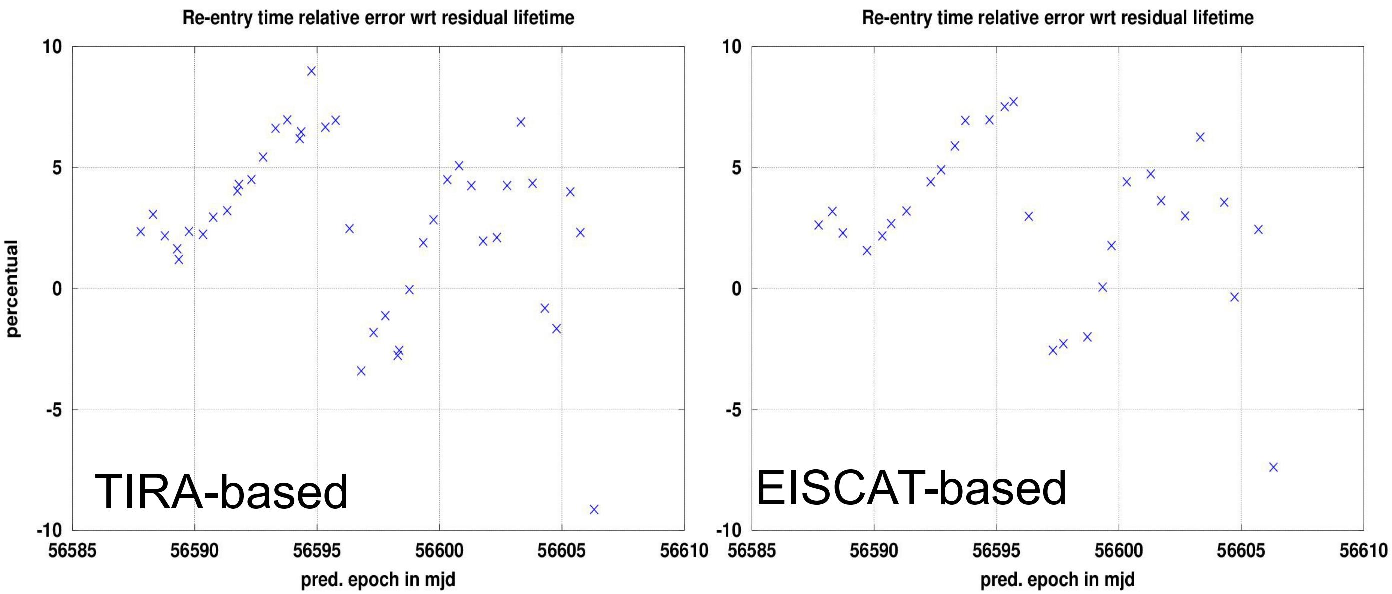
Initial element	Variation interval	Corresponding variation of re-entry epoch w.r.t. nominal residual lifetime (percentual)
a	$\pm$ 300m	< 1.0%
e	$\pm$ 3x10^{-4}	< 0.5%
ω+*M*	$\pm$ 0.1°	< 0.5%
i	$\pm$ 0.01°	< 0.01%
Ω	$\pm$ 0.05°	< 0.01%

$$\epsilon_{re} = \frac{t_{re} - t_{re}^{true}}{t_{re}^{true} - t_{pred}} \cdot 100$$

- We can see from the results that both TIRA and EISCAT radar-based OD solutions provide orbital errors that **do not change significantly** the predicted re-entry epoch. Similar results hold also for a prediction epoch closer to re-entry.

OD errors and variation of re-entry time

The errors in re-entry predictions during the simulated campaign reach ~**10%** of residual lifetime, and are not mainly due to OD inefficiencies. They are dominated by the average mis-modelings occurring in the time span from the prediction epoch to the actual re-entry.



They can be due to **unpredicted significant attitude changes** and **unmodeled atmospheric density variations**.

The **choice of the observation time span is crucial** to reconstruct the main variations of the ballistic coefficient. There is no a-priori best choice for the calibration interval, different ones should be used.

The correctness of the prediction mostly depend on what happens **after the prediction epoch:** one issue is to understand, from the calibrations up to the current one, what is the general attitude behaviour of the object (e.g. stable, tumbling) and try to predict if major changes can occur afterwards. However, this can be quite difficult.

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Main conclusions I

Given a decaying object in low eccentric and highly inclinated orbit:

1) Provided a **minimum amount of necessary observations**, EISCAT-based re-entry predictions are of comparable accuracy to TIRA-based corresponding ones.
2) The **EISCAT sensor** proved to be a **valuable and effective resource** to support OD and re-entry predictions.
3) The worse tracking capabilities of EISCAT provide less accurate orbits w.r.t. TIRA, but the estimated orbits are equivalent in terms of re-entry predictions, if we consider the relevant parameters involved and their effects on the re-entry time.
4) If possible, **different observation time spans** should be used to calibrate the ballistic coefficient variations.
5) What remains to be very important is the **difficulty in predicting** both atmospheric and attitude significant variations in between the current epoch of observation and the actual re-entry.

Main conclusions II

Results not presented here, and more details, are contained in

“Cicalò S.,Lemmens S., 2018, Radar-based Re-entry Predictions with very limited tracking capabilities: the GOCE case study”, paper in preparation:

1. **Real radar observation environments** have been tested as well, with also **TLEs** exploitation, obtaining consistent results.
2. Some **critical scenarios** which consist in a too little amount of observational information, or in difficulties in obtaining OD convergence, were tested, and a list of possible countermeasures was proposed.
3. Tests with few objects with different attitude behaviour have been performed, obtaining consistent results.
4. Future activities on this topic shall include analogous analysis for objects in more eccentric orbits, and/or with several different shapes and attitude motion.

Extra Slides

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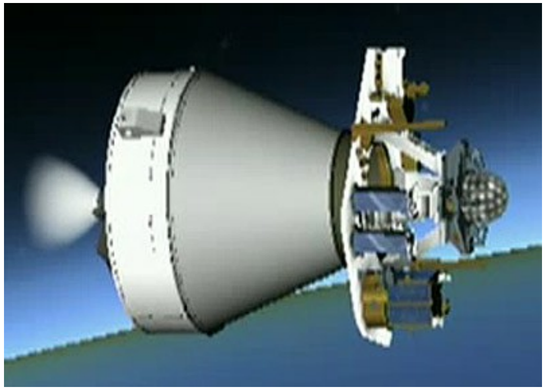
2012-006K AVUM R/B radar data

TIRA and EISCAT UHF **real data** have been processed to compute re-entry predictions for **2012-006K**.

According to the ESA DISCOS database, the 2012-006K AVUM rocket body had a nominal mass of 960kg, with an approximate shape of $1.9x1.7x1.9m^3$, and an average cross sectional area of $2.162m^2$.



Pass	Obs type	Data start UTC	Data end UTC
TIRA1	r, rr, az, el	2016-10-20 14:50:06	2016-10-20 14:56:09
EISCAT1	r, rr	2016-10-21 16:19:48.98	2016-10-21 16:19:50.38
EISCAT2	r, rr	2016-10-22 16:09:53.32	2016-10-22 16:09:55.50
EISCAT3	r, rr	2016-10-22 19:12:27.81	2016-10-22 19:12:29.88
EISCAT4	r, rr	2016-11-01 15:59:48.26	2016-11-01 15:59:50.00

2012-006K AVUM R/B re-entry predictions

- We have combined three radar-based re-entry prediction scenarios, summarized below:

#scen	passes	total obs ΔT	Residual lifetime from last obs. to nominal re-entry (2016 11-02)
1	TIRA1 + EISCAT1	~25h	~12d
2	EISCAT1 + EISCAT2 + EISCAT3	~27h	~11d
3	TIRA1 + EISCAT1 + EISCAT2 + EISCAT3	~52h	~11d

#scen	use of AP on in.cond. (TLE-based: 1km pos,1m/s vel)	RMS of residuals	estimated CdA	Re-Entry epoch (at 90km)
1	YES (not mandatory)	TIRA1(r,az,el): 10.4m, 0.0059°, 0.0067° EISCAT1(r,rr): 11.7m, 1.8m/s	8.8373 m^2	11-03 ~19:56 UTC
2	YES	EISCAT1(r,rr): 11.1m, 1.8m/s EISCAT2(r,rr): 11.5m, 1.1m/s EISCAT3(r,rr): 9.6m, 1.0m/s	8.7332 m^2	11-03 ~22:00 UTC
3	YES (not mandatory)	TIRA1(r,az,el): 13.5m, 0.015°, 0.014° EISCAT1(r,rr): 66.8m, 4.5m/s EISCAT2(r,rr): 28.8m, 11.5m/s EISCAT3(r,rr): 17.7m, 6.3m/s	9.0684 m^2	11-03 ~11:51 UTC

2012-006K AVUM R/B radar+TLE data

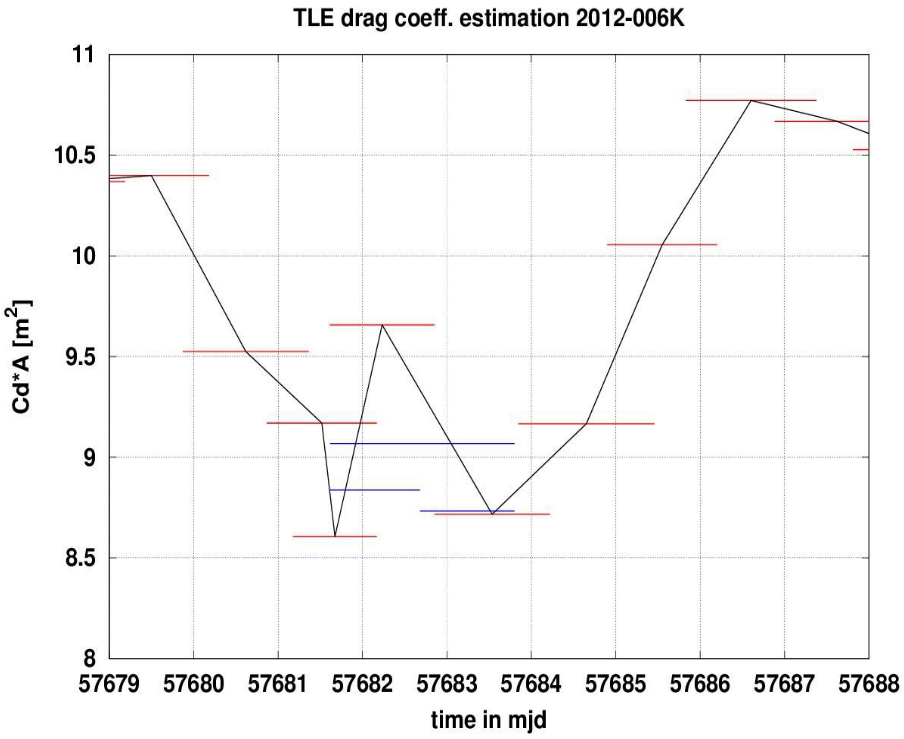
In order to exploit also the fourth EISCAT track, very close to re-entry, we have combined it with two additional USSTRACOM TLEs, summarized below:

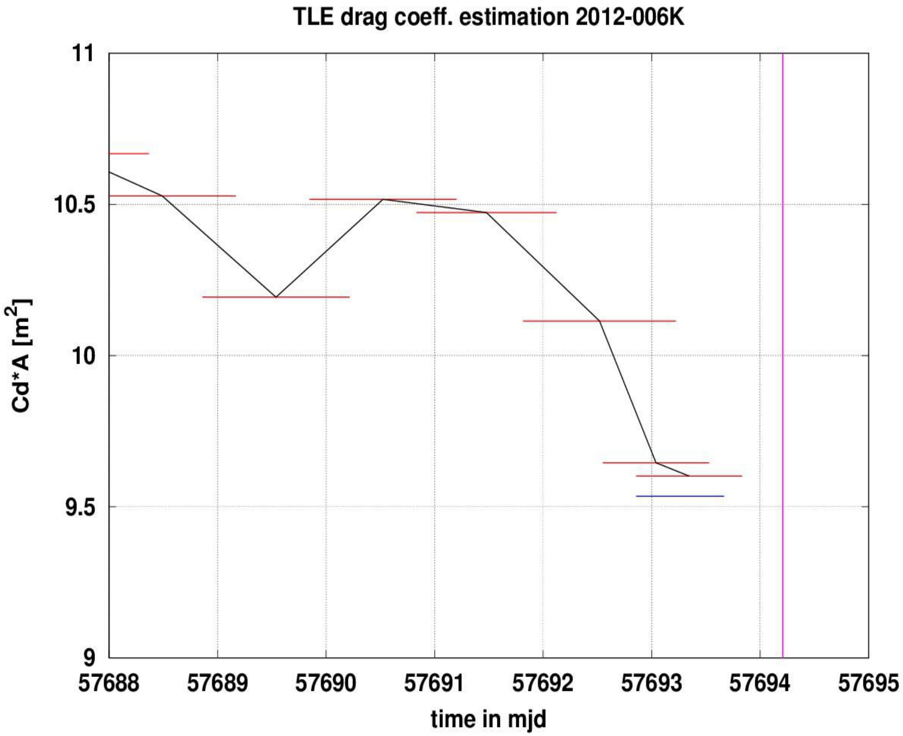
#scen	data	total obs ΔT	Residual lifetime from last obs. to nominal re-entry (2016 11-02)
4	TLE1(epoch oct31~20:32pm) + TLE2(epoch nov1~03:53am) + EISCAT4	~19h	~12h

#scen	RMS of residuals	estimated CdA	Re-Entry epoch (at 90km)
4	TLEs(pos,vel): 170m, 0.2m/s EISCAT4(r,rr): 12.9m, 1.8m/s	9.5235 m^2	11-02 ~04:57 UTC

2012-006K TLE-based calibration

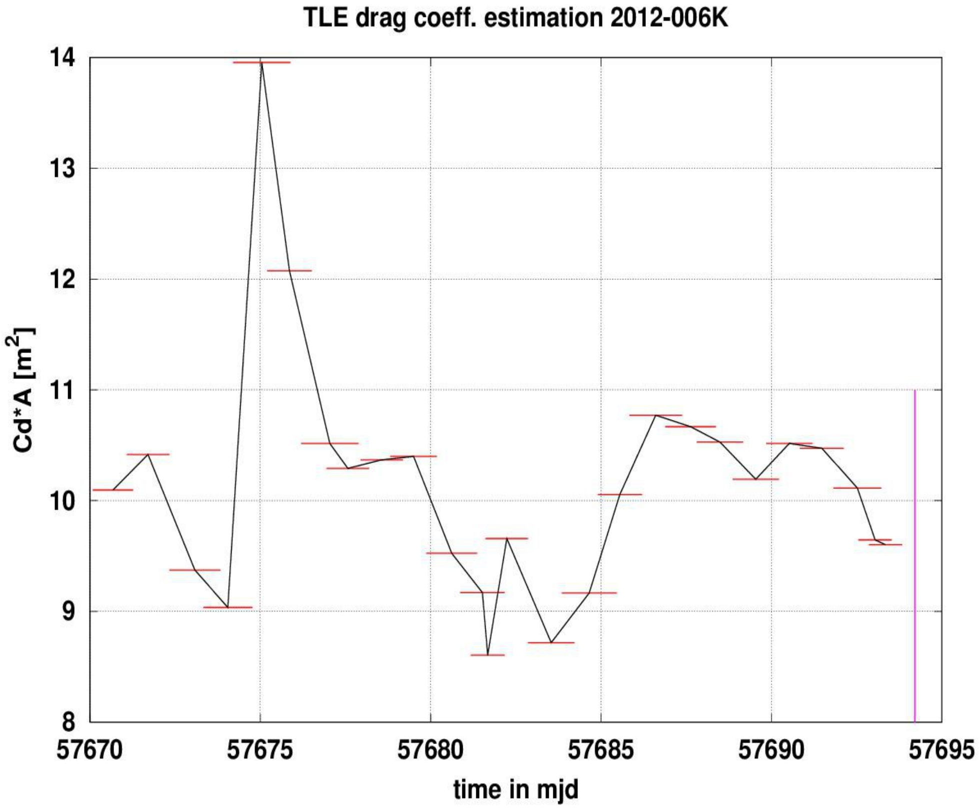
TLE-based ballistic coefficient calibrations obtained by **TLE fitting** over time intervals of ~24-36h (in red), compared with the 4 previous scenarios calibrations (in blue):





2012-006K TLE-based calibration

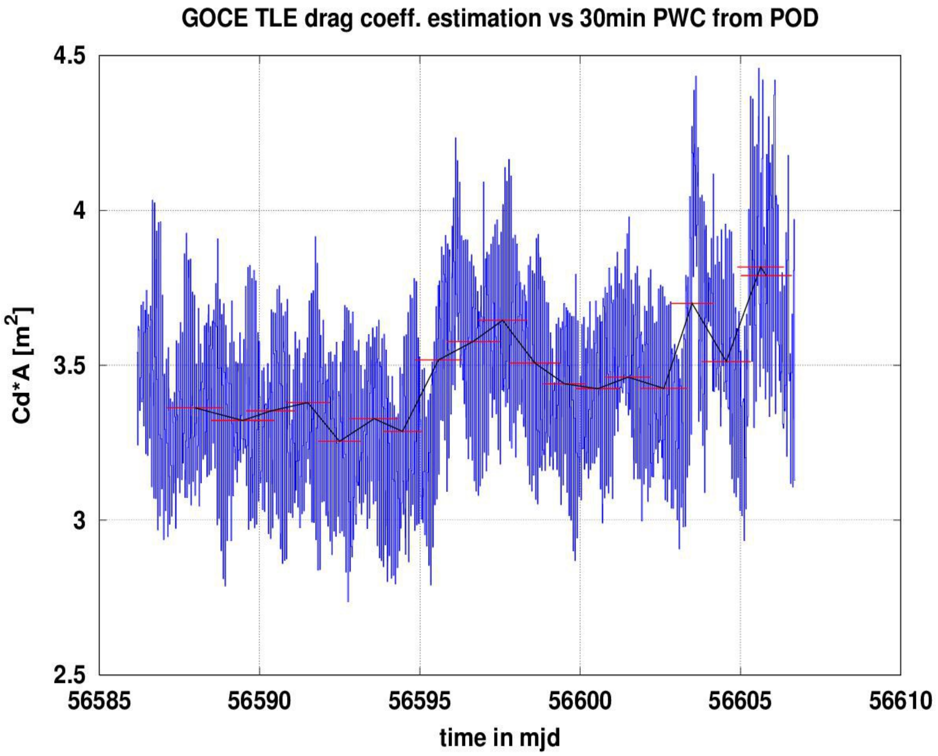
TLE-based drag coefficient calibrations obtained by TLE fitting over time intervals of ~24-36h (in red).



More investigation may be necessary to explain the variations.

GOCE TLE-based calibrations

GOCE TLE-based ballistic coefficient calibrations obtained by TLE fitting over time intervals of ~36h (in red), compared with POD-based 30min PWC coefficient (in blue).



The ballistic coefficient relative difference (in percentual) w.r.t. the mean of the 30min PWC coefficient over each observation time span is **below 3%**.

GOCE re-entry campaign–critical scenarios

There are some **critical cases** for which the **standard OD and ballistic calibration does not work properly**.

1) First, if we have **less than 4 very short tracks from EISCAT**, of range and range-rate, the solutions are in general bad determined (or even ill-posed).

2) Second, if we are performing **OD close to re-entry**, even if we have enough observational data to compute a full solution and good initial conditions, in some cases the dynamical systematic errors are particularly strong to introduce instabilities in the differential corrections ("*overshooting*") and even **divergence**. (E.g. this problem can occur for TIRA data processing, when we try to fit all the last 5 TIRA passes together, time span ~48h).

Critical cases possible countermeasures I

Only two EISCAT passes

1) Ask for the **additional availability of a TIRA track**.
   The information contained in the TIRA pass, combined with the two EISCAT passes and a good initial condition (e.g. TLE-based), will lead to a more stable problem and possibly to a good OD and ballistic coefficient estimation.

2) If the initial conditions have a reliable error estimation, then imposing an **a-priori constraint on the initial position and velocity** will lead to a more stable problem and possibly to a good OD and ballistic coefficient estimation.
   E.g., TLE initial condition with ~1km constrain in position and ~1m/s in velocity.

Only three EISCAT passes

3) It is quite similar to the previous one, and it can be treated in the same way.

4) We have considered only range and range-rate short tracks, without assuming any information for the **azimuth and elevation angles of the tracked object**.
   If confirmed, a quite low accuracy information could be deduced from the radar pointing direction, for example to the 1-2° level. Adding this information on the direction of the tracked object would help in stabilizing the problem and possibly lead to a good OD and ballistic coefficient estimation.

Critical cases possible countermeasures II

Unstable differential corrections

When we approach the re-entry, the altitude decreases and the **modeling errors in the non gravitational perturbations grow** in magnitude causing large errors in the estimated orbits.

Given a proper observational scenario, it is possible to find a **good solution for re-entry predictions** anyway, at the cost of obtaining **large residuals** with respect to observational noise.

In some cases, even with enough observational data, and good initial conditions, it is difficult to compute a full OD and ballistic coefficient estimation because the problem shows **instabilities**, and the differential corrections **diverge** (***overshooting*** *effects*).

This problem is possibly due to a combined effect of intrinsic, even small, weaknesses in the OD covariance matrix, and particularly large systematic dynamical errors which affect the residuals.

We have tried at least **three strategies** that could help in leading the problem to converge, or at least to approach to a good solution:

1) Damped differential corrections (under-relaxation),
2) Differential corrections with pseudoinversion (descoping),
3) Use of a-priori constraints on initial conditions with deweighed observations.

Critical cases possible countermeasures III

We now briefly describe how these strategies can be applied, to give an idea on what are the main formulas involved:

$$B_x = \partial\xi/\partial x\,,\ C = B_x^T W B_x\,, \Gamma = C^{-1}\,, D = -B_x^T W \xi$$

$$x_{k+1} - x_k = \Delta x = \Gamma D$$

1) Damped differential corrections.

$$\Delta x = \Gamma D/\alpha\,, \alpha = MAX(1, n-k+1)$$

2) Differential corrections with pseudoinversion.

$$\Gamma = U E^{-1} U^T\,, U = [v_1..v_N]\,, E = diag(\lambda_1, .., \lambda_N)\,, U U^T = I\,, \lambda_1 < .. < \lambda_N$$

$$\Delta x = \Gamma' D\,, \Gamma' = U E^{-1\prime} U^T\,, E^{-1\prime} = diag(0, \lambda_2^{-1}, .., \lambda_N^{-1})$$

3) A priori constraints on initial conditions with deweighed observations.

$$W \longrightarrow W/\beta^2\,, \text{and a-priori } \{[\mathbf{x}, \mathbf{v}] = [\mathbf{x}_0, \mathbf{v}_0]\,, \Gamma_{AP}\}$$

where β is a suitable tuning parameter.