EXPRO+ GOCE Benchmarking Re-Entry Prediction Uncertainties

Executive Summary

January 2017

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Acronyms and Abbreviations

3 (6) DOF	3 (6) Degrees Of Freedom
AD	Applicable Document
ATC	Attached document
BRL	Belstead Research Limited
CFI	Customer Furnished Item
CPR	Cycle Per Revolution acceleration
ESA	European Space Agency
EXS	Executive Summary
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
GREOD	GOCE Re-Entry Orbit Determination software
GSP	General Studies Programme
HDMR	High Dimensional Model Representation
IERS	International Earth Rotation Service
IGS	International GNSS Service
JB08	Jacchia-Bowman 2008 density model
JRs	Jacchia-Roberts static density model
NRLMSISE00	United States Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar density model
OD	Orbit Determination
PDF	Probability Density Function
POD	Precise Orbit Determination
PSO	Precise Science Orbit
PWC	PieceWise-Constant
RD	Reference Document
RMS	Root Mean Square
RREO	Reference Re-Entry Orbit
RTW	Radial - Transversal - out of plane reference system
SSTI	Satellite to Satellite Tracking Instrument
STD	Standard Deviation
STR	Star Tracker
UOS	University Of Strathclyde
UP	Uncertainty Propagation
UQ	Uncertainty Quantification
WBS	Work Breakdown Structure
WP	Work Package

1 Introduction

This document is the Executive Summary of the ESA EXPRO+ "Benchmarking re-entry prediction uncertainties" project. It is created in the frame of the ESA GSP, which aims at preparing the groundwork for the agency's future activities.

This EXS is based on the project's SOW [AD05], and it refers to the Technical Notes [ATC02], [ATC01], [ATC04], [ATC05] and [ATC03]. The document provides a concise summary of the project objectives of the project, including the obtained results, the lesson learned, and the possible evolution of the work.

1.1 Project's background

The project is dedicated to an in-depth study of the re-entry of the ESA’s Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite, for which a rich measurement data set is available up to the very end of its decay phase.

The GOCE spacecraft reached fuel depletion on Oct. 21st 2013, at an altitude of about 225km. As a result, GOCE started a natural decay which led to an uncontrolled re-entry on Nov. 11th 2013 at 00:16UTC (atmospheric altitude ~80km). Incredibly, the spacecraft was still, most likely, fully functional for all the duration of the decay, apart from its "drag-free" control system. This yields a rich dataset, that contains in particular a continous set of GPS measurements and attitude states, that has been collected by the spacecraft and downloaded up to the last pass down to altitude of about 100km. Independent of ESA, many other sensors have followed GOCE during its decay phase, such as satellite laser ranging and ground-based radar systems (e.g. FHR TIRA).

1.2 Project's main purposes

The project's main purpose is to exploit the extremely reach measurements data set of GOCE until the very last day of its atmospheric re-entry, in order to improve the general understanding in the field of satellite re-entry predictions. In particular, the very good quality and accuracy of the GPS and attitude measurements would allow a Precise Orbit Determination (POD) of the spacecraft down to very low altitudes. Such a precise reference orbit could then be exploited to assess the quality of external measurements (e.g. radar-based tracking data) and to characterize the corresponding re-entry predictions uncertainties. Moreover, the possibility to simulate artificial measurements on the reference orbit can be exploited to investigate the potential for reduction of the uncertainties. In general, even with perfect observation capability, the theoretical uncertainty of any re-entry prediction will still be influenced by the evolution of the atmosphere. This activity thus needs to analyse this effect.

Eventually, given the aerodynamic shape of GOCE, the study shall investigate the extent to which the results of the analysis can be extended to long cylindrical objects with fixed centre of mass versus centre of gravity pose, e.g. rocket bodies. This specific configuration can under certain conditions lead to attitude stabilisation and, if anticipated correctly, give rise to increased accuracy in the re-entry predictions.

1.3 Project's work logic

According to the main guidelines given in [AD05], the project's main tasks can be summarized in the following way:

- **Task 1.** Re-construction of the GOCE orbit, in the sense of POD, and estimation of related uncertainties during the last weeks of operations until the end of GPS observations.
- **Task 2.** In depth analysis of the re-entry prediction uncertainties by sampling from the re-constructed GOCE orbit, as well as simulating observations along this orbit and performing the orbit determination, and propagating orbit and attitude till re-entry. This includes varying the environment characteristics during the re-entry propagations as a sensitivity analysis, and formulating a re-entry observation planning which minimises the prediction uncertainties stemming from the OD process.
- **Task 3.** Evaluate the applicability of the uncertainty analysis to the re-entry of other large objects.
- **Task 4.** Assess if the generally accepted uncertainties on re-entry predictions can be reduced by enhancing our understanding of the environment and prediction techniques.

2 Results

In this section we summarize the main results achieved within the first three tasks of the project.

2.1 Task 1: High Accuracy Orbit Determination and Aerodynamic Analysis

First of all, a Precise Orbit Determination from GPS satellite-to-satellite measurements has been performed and reported in [ATC02], along with a sensitivity analysis on different empirical models adopted to treat un-modeled perturbations, on different atmospheric density models, and on orbit determination techniques during data gaps. What OD is expected to do is to extract information from the available observations, in order to correct and update the orbital evolution of the spacecraft, possibly estimating also other uncertain physical quantities. In the POD framework, the extremely demanding level of accuracy and the availability of continuous measurements requires and allows for a dense empirical parametrization of the dynamical perturbations, capable to absorb un-modeled effects. On the one hand, this results in an effective way of reducing the observations residuals and correctly model the orbital motion of GOCE. On the other hand, a simple interpretation of the estimated empirical parameters in terms of physical meaning is very difficult. As a general result, under the strong perturbations of the last days of re-entry, the POD turns out to be very sensitive to the choice of the empirical accelerations model, while different assumptions on the atmospheric environment seem to be absorbed quite well by the fitted parameters, without affecting the orbit determination too much. In case of large data gaps, the problem is again to find a way to absorb unmodelled effects. A constrained multi-arc strategy was proposed, that allows for OD during data gaps. This technique turned out to be quite useful only under certain circumstances, and to be in general strongly dependent on the size of the gaps.

All the necessary analysis on the GOCE vehicle aerodynamics, and its atmospheric interactions, has been reported in [ATC01], starting from the available shape models. A range of static and dynamic atmosphere models has also been assessed. The forces predicted by the combination of the atmospheric and aerodynamic models have been found to be consistent with the available force data. This has been analysed during the large yaw events identified in the last days of re-entry, and the data has been shown to fit well with an aerodynamic resonance hypothesis. Aerodynamic databases have been constructed, and the main features of the parameters affecting the generation of drag have been assessed.

More specifically, the analysis included effects of speed ratio, gas-surface interaction and the relative importance of pressure and shear drag contributions at different attitudes. From this analysis, a clear signal was obtained from the speed ratio and the attitude, but the effect of the accommodation coefficients could not be correlated with the data.

From the calculated aerodynamic moments, an approximate aerodynamic frequency has been calculated. This frequency agrees very well with the increasing frequency seen in the power spectrum of the yaw motion in the final few days (see [ATC06]). Preferred frequencies at each orbital harmonic can be seen, and there is an increased response as the aerodynamic frequency passes through three, four and five times the orbital frequency. Larger yaw has been observed at these times, resulting in increased drag. This work proposes that these larger yaw events are a result of resonance between the aerodynamic and orbital frequencies. However, these events also coincide with increased geomagnetic activity, which has also been proposed as a cause of the larger yaw motion. Further, the large response at the orbital frequency has been identified as an interaction with the planetary spin rate for a polar orbit.

The possibility that the larger yaw events are driven by resonances is interesting, as with some data on the vehicle, these could be predicted and the re-entry predictions, and uncertainties, could include this effect. The unpredictable nature of geomagnetic activity would preclude such model refinement if it is confirmed as the cause of the large yaw events.

The aerodynamics of the GOCE vehicle have been assessed by running baseline cases using the ATS6 6DOF trajectory code. It has been found that the behaviour over short arcs is comparable with the observation data, but that over longer periods the vehicle would be expected to tumble when at the higher altitudes of the first week of re-entry. This results in re-entry predictions which are substantially earlier than those seen in reality. The difference is due to the GOCE control system which remained functional throughout the re-entry, and especially its suppression of any roll motion, for which the spacecraft has been observed to be unstable.

When providing uncontrolled re-entry simulations where a reasonable assessment of the uncertainties in comparison with the observed data is required, the original vehicle geometry and mass properties are only appropriate for assessments of a few days. Therefore, attempts were made to represent the control system using a simplified model and to assess the behaviour which can be generated by adjusting the mass properties of the GOCE vehicle. Neither of these approaches was fully successful in producing a baseline which can be used for a sound uncertainty analysis over the full 20-day entry period. Therefore, use of a simple cylindrical geometry was proposed for longer term uncertainty analysis.

2.2 Task 2: Radar-based Orbit Determination and Re-Entry Prediction Uncertainty Analysis

We have investigated the performances of radar-based OD and corresponding re-entry predictions [ATC05], making use of the POD as ground truth for realistic simulations. Both in the GPS-based POD framework and in the radar-based observational scenario, the main conclusion is that the errors/uncertainties in the dynamical models dominate by far the problems in the observational features. As widely known from the relevant literature, the problem of correctly modeling drag consists in computing the fundamental product $\rho\, C_d\, A/m$, where ρ is the atmospheric density at spacecraft's location and time, A is the cross-sectional area exposed to the flow, m is the spacecraft's mass, and C_d is the coefficient of drag which depends on the satellite's shape and orientation, flow conditions and surface chemistry effects. Each of these parameters has its own error budget, which depends both on intrinsic uncertainties and on the quality of information currently available. Roughly below 200km, when the drag perturbations exponentially grow because of the atmospheric density increase, the magnitude of the perturbations due to errors/uncertainties in drag modelling increases as well, determining larger and larger variations of the propagated orbit with respect to the real one. In the framework of radar-based observational scenarios, where the required accuracies are lower than the ones of GPS-based POD, a simple analysis in terms of average drag estimation is possible.

Radar measurements can be used to perform standard OD and ballistic coefficient estimation for re-entry predictions [RD15]. The POD can be used both for orbit comparison and for an accurate and more refined extrapolation of the ballistic coefficient evolution (see [ATC05]). The corresponding extrapolation made only with radar measurements was studied in depth, both with real data from the TIRA sensor of the Fraunhofer institute for High Frequency Physics and Radar Techniques, and making an extensive use of a radar-data simulator, which can generate artificial observations from further ground stations, using the POD as ground truth.

The main result is that, with a reasonable frequency of measurements, radar-based OD is very effective in estimating the average evolution of the spacecraft's ballistic coefficient, in comparison to the one estimated from POD, even from a single site (TIRA). It makes even possible to capture the significant variations in the spacecraft's attitude (large yaw events) during the last days of re-entry. It turns out that, especially during the last two days, it is impossible to fit many radar tracking passes at the level of accuracy expected by the instrument quality (e.g. tens of meters in range, centidegrees in azimuth/elevation STD), (see [ATC05] Tab.4). The lesson learned is that the high accuracy provided by GPS-based POD hides the intrinsic large errors in the dynamical models, atmospheric environment, and attitude behaviour, which are absorbed by the fitted empirical accelerations. These errors re-appear instead in the radar-based OD under the form of large observational residuals during the last days, where the observations are sparse, the un-modeled perturbations grow significantly, and cannot be fully absorbed by a constant ballistic coefficient correction.

Typical empirical uncertainties related to re-entry predictions during the last weeks of a space object are at the order of $\pm 20\%$ in the time from the last observation available to actual re-entry. Besides an unavoidable component due to the measurement errors, a significant part of the uncertainty quantification comes from the object's physical characteristics, attitude motion, accuracy and prediction of the environment variables at low altitudes, and dynamical mis-modelings in general. The GOCE re-entry example not only confirms this level of uncertainties, but it also highlights the fact that even with very accurate and abundant measurements it is not possible, or at least not easy, to generate very accurate re-entry predictions. In other words, even with a very good knowledge of the position and velocity of the spacecraft, and with a good ballistic coefficient evolution estimation, in general it is not possible to deterministically predict the re-entry location with very high accuracy (e.g. always much better than 10%). For this reason, since the re-entry time uncertainty window is typically constrained in relative value, guaranteeing observational sessions up to few hours before re-entry is always recommended to reduce the size of the re-entry window. This fact is one of the most important aspects related to the observational sensor architecture: provided at least standard accuracy sensors (e.g. ~30m in range and ~0.03° in azimuth/elevation noise STD), in order to increase the visibility frequency of a polar orbiter, more stations, well distributed in longitude and preferably at medium-high latitude, are necessary.

The problem of the propagation and quantification of the uncertainties associated with re-entry predictions, with suitable advanced models, is reported in [ATC04]. The use of global sensitivity analysis approaches has allowed to point out the relative influence of each single uncertain parameter with respect to the others, stressing the importance of the model, and model parameters, over the initial states. Moreover, the analyses confirmed that the output probability density distribution cannot be considered uniform, generally being a skewed normal.

At the start of the work, 1D and multivariate sensitivity analyses, as well as uncertainty propagation (UP) analyses were performed, considering uncertainties on initial conditions (position, velocity, attitude and attitude rates), and atmospheric and shape parameters, such as a “density multiplier” that represents both the multiplicative uncertainties on the C_d and on the modeled density, the logarithmic geomagnetic index, Kp, and the solar flux index, F10.7. For the analyses, three initial conditions along the re-entry trajectory of GOCE – 2 days, 10 days, and 20 days after the start of the decay phase – have been propagated. No control was implemented in the 6DOF re-entry code, meaning that a direct comparison between the 6DOF based results and the data of the actual GOCE re-entry was not possible.

The initial 1D analyses over an extended range of the considered parameters was carried out to explore the effect of each single uncertainty and, especially, quantify the range of (uniform) uncertainty that would give a re-entry time window at the level of the +/- 20% (of the nominal/deterministic value) assumed in the currently used margin approach. Results reported for the three initial conditions using the 3DOF code highlighted how the effect of each single uncertainty may vary during the decay phase: 1) for all the three conditions the relative re-entry time window is a linear function of the uncertainty range; 2) for uncertainties on the initial positions, the effect on the relative re-entry time window is higher the more the object is closer to the re-entry condition; 3) the effect of the density multiplier is substantially the same for all the three cases; 4) the effect of geomagnetic and solar flux indexes is lower the more the object is closer to the re-entry condition. Results obtained by using 6DOF and 3DOF codes for the same nominal initial conditions stressed the highly non-linear effect of the uncertainties, due to the sensitivity of the re-entry time to the dynamics of the uncontrolled object. Results obtained by considering the uncertainty on initial attitude and attitude rate conditions point out that there is a range close to the nominal conditions where the relative re-entry time window is a non-linear but smooth/treatable function of the initial condition, and that outside the close range, the behavior becomes highly non-linear and almost chaotic.

Different intrusive and non-intrusive approaches (including Monte Carlo sampling) have been used to perform UP and multivariate sensitivity analyses. Obtained results have pointed out the shape of the probability density function (PDF) for the re-entry time when different models and different initial conditions are considered, as well as the relative effect of different uncertainties (and combination of uncertainties) on the overall PDF. When the 3DOF model is considered, the output PDF can be approximated by a skewed normal distribution for all the initial conditions. The smooth distribution was well managed/approximated by the used non-intrusive methods, based on the high dimensional model representation (HDMR) and on the non-intrusive Chebyshev interpolations, and the use of the HDMR based method allowed to highlight the contribution of the different uncertainties – as well as combination of uncertainties - for different test cases. In particular, it emerged that the effect of initial position and velocity components can be of secondary importance, with respect to the atmospheric and model uncertainties, when the uncertainty ranges are obtained from standard OD processes. When the 6DOF model is considered, the function linking the re-entry time to the considered uncertainties or the uncontrolled GOCE is multi-modal, resulting into a non standard PDF with multiple peaks. The number of local minima and maxima of the re-entry time hypersurface is so high that the approximated methods for UP are not efficient with respect to MC sampling, if we want to catch all the peaks of the PDF. Many tens of thousands samplings are needed to properly model the PDF, but still, such a high number of samplings is not enough to properly catch the tails and, especially, the extreme values, of the PDF. For all the cases where the output distribution has long tails, it is still unclear how to use the obtained information: which part of the tails can be neglected to have reasonable characterisation of the re-entry time window without being too conservative?

An intrusive method based on Chebyshev interpolation – as well as Taylor interpolation for comparison purposes - has been implemented and used to perform uncertainty quantification on GOCE's trajectory as well. Both Chebyshev and Taylor intrusive methods are applied to a 3DOF orbit propagator, and results on test cases demonstrate the efficiency of the approach when compared to classical MC sampling approach. Due to the complex drag model implemented, the use of the intrusive technique represents a non-trivial application of a novel method in space flight dynamics that demonstrated more robustness than the classic Taylor expansion.

Two different uncertainty quantification/characterisation approaches have been also proposed during the project. The same interpolation techniques used for non expensive non-intrusive methods for UP, allowed the development of two methods based on direct optimisation approaches: *Boundary Set Approach* (BSA) and the *Inverse Uncertainty Quantification* (IUQ). Given a trust-interval I on the re-entry time, the BSA derives the largest ellipsoid such that all occurrences of the uncertain parameters contained in this region lead to a re-entry time within the desired bounds. Instead of the full orbit propagator which is too computationally expensive intense to run, its non-intrusive Chebyshev surrogate is used to evaluate the re-entry time. The computation of the ellipsoid is done in three major steps. First, a series of optimisation problems is solved in order to find points on the boundary i.e. where the re-entry time reaches the fixed limits. Then a principal-axis analysis is performed on this set of points. The result determines the axis and aspect ratios of the final ellipsoid. The last step consists in an iterative search for the largest possible size of this ellipsoid. On the other hand, given a probabilistic distribution for the time of re-entry, the IUQ approach lets to infer the structure of the corresponding input distributions. This is done through, again, an optimisation process, which minimises the difference between the required output distribution and the output distribution obtained by the propagation of the parametrised input uncertainties. Methods have been proposed and tested, but not fully exploited: most of the analyses were carried out by using approximated UP techniques and there still is no clear idea on the objective functions to use.

2.3 Task 3: Rigid-Body Dynamics

In the third task of the project, we have performed a comparison between the GOCE rigid-body re-entry dynamics with equivalent cylinders, other simplified satellite shapes, and real re-entry data [ATC03]. A consistent pattern of attitude behaviour during re-entry has been observed.

Whilst investigating the re-entry behaviour of an aerodynamically stable cylinder which maintains stability from an altitude of 230km to final re-entry, some tests were carried out with a higher altitude initial condition. In these simulations it was observed that the cylinder was unable to maintain stability and began tumbling significantly before an altitude of 230km was reached. This suggested that before the behaviour of objects starting in a stable, aligned condition were analysed, some effort was required in determining whether such a stable attitude could be established in the first place. To do this, a range of objects, such as equivalent cylinders, simplified satellite shapes and the GOCE vehicle itself have been assessed from a range of initial orientations. The initial conditions include aerodynamically stable alignment, aerodynamically unstable alignment and gravity gradient stabilised alignment. Some conditions were observed where an initial stable alignment could be maintained, but none where such a stable alignment could be generated from any other initial condition prior to approximately 48 hours before final re-entry.

For all of the tested shapes, a consistent pattern of attitude behaviour during re-entry was observed. This has the following stages:

- Initial alignment to gravity gradient orientation can be maintained for most vehicles tested, although this is not the case for vehicles with a without a dominant principal moment of inertia, or vehicles on sufficiently elliptic orbits.
- As drag increases, the attitude of the vehicle is pulled towards an aerodynamically stable orientation, thereby losing the gravity gradient stability. However, an aerodynamically stable orientation cannot be established and the vehicle tumbles. This transition occurs at higher altitudes for vehicles with higher aerodynamic stability characteristics as the aerodynamic torques are larger.
- This tumbling motion is maintained until the final stages of the re-entry when the aerodynamic forces are sufficiently large to allow the vehicle to enter a coning motion. Typically, this stable motion affects the final 24-48 hours of the re-entry

It has also been shown that an initial aerodynamically stable attitude can be maintained in the absence of a gravity gradient torque for simple vehicles. However, if the initial condition is not close to a stable attitude, then the stable orientation cannot be established until altitudes below 200km are reached. The results further suggest that 3DOF tumble averaged drag, calculated by averaging the drag over all angles of incidence, provides a very good estimate of the drag for the majority of the re-entry. This, in turn, suggests that current ballistic coefficient based shooting methods are essentially a good baseline approach. The alignment in the final days has been the cause of larger errors, but this analysis suggests that a vehicle specific adjustment to a 3DOF model could be proposed without the need for a full 6DOF analysis. This observation is consistent across the vehicles tested.

Assessment of the TLE data from a number of rocket body re-entries has shown that the dominant factor in producing a reasonable re-entry prediction is the ballistic coefficient, and that a tumble averaged value again provides the best estimate for the majority of the trajectory. Significant effort has been put into attempts to generate feasible conditions in which the vehicle could be predicted to have aligned, but none of these are realistic. Moreover, the simplified cylindrical aerodynamic model, which would be expected to be more stable than a more general geometry, always showed tumbling to be induced. In order to match the trajectories obtained from rocket body TLE data, the mass of the vehicle was seen to be the dominant parameter, essentially equivalent to estimating a ballistic coefficient from the data. Whilst the mass adjustment was a significant proportion of the vehicle dry mass, it was seen to be less than 10% of propellant mass in all cases. As a consequence, it is suggested that, given the elliptic nature of the orbits examined, the bodies are tumbling with the mass necessary to achieve the observed ballistic coefficient being residual fuel. The analysis is consistent with the other shapes tested in that the vehicles are expected to tumble until the final days of re-entry. Again, the tumbling was well represented by a 3DOF tumble averaged drag in all cases.

In the majority of cases, some alignment of the 6DOF motion was observed within the final 24-48 hours of the re-entry. Although only a correlation at this stage, this is consistent with the observations that the ballistic parameter is often seen to increase substantially in the final days of the re-entry, before stabilizing at a higher value. This would be consistent with the transition from an essentially tumbling high drag motion to a stable coning motion with a lower mean projected area. In cases where something is known of the vehicle geometry, an estimate of the potential for alignment, and its effect on the time to re-entry, could be made, potentially improving re-entry time predictions.

3 Critical Assessment

In the framework of the OD and parameter estimation analysis, three main observational scenarios have been considered for a polar orbiter decaying in the lower thermosphere: continuous GPS and attitude measurements, single-sensor and multi-sensor radar observations. All the three scenarios have the following aspects in common:

- below ~200km altitude the OD errors are dominated by the deficiencies in the dynamical models rather than in the observational features;
- part of the un-modeled effects can be absorbed by a more dense (POD) or less dense (radar-based OD) empirical parameters estimation, giving information on the object's behaviour that can be used to calibrate future propagations;
- residual errors in the parameter estimation, in particular in the average ballistic coefficient, always remain, because of the intrinsic uncertainties in the atmospheric models;
- for future re-entry predictions, the contribution from the initial uncertainties in position, velocity and ballistic coefficient must be added to the contribution from the uncertainties in the prediction of the atmospheric environment (intrinsic density errors variations, solar flux and geomagnetic storms extrapolation, winds), and in the prediction of the attitude behaviour (e.g. start of tumbling or alignment from tumbling at a certain point).

In the light of the results achieved in this study, we believe that the following aspects are of primary importance to improve the computation of reliable re-entry predictions in the lower thermosphere (90-200km):

- either we improve the accuracy in the atmospheric environment models, or we improve the corresponding error model;
- until the very last day of decay, a moderate availability of standard radar-based observations, even from a single site, is a fairly good method to calibrate re-entry predictions with the standard ballistic shooting method, provided that the tracking passes are combined properly;
- in order to guarantee a reasonably small re-entry window during the last part of decay, an observational sensor architecture capable of guaranteeing a higher frequency of measurements in the last ~24-hours would be recommended. For a polar orbiter like GOCE, this translates, for example, in radar sensors available at medium-high latitude and well separated in longitude;
- provided that enough information on the shape and physical characteristics of the object is available, the results from the 6DOF aerodynamic analysis [ATC03] could be exploited and checked in (almost) real-time with the OD results, at least from a qualitative point of view (e.g. aligment from tumbling behaviour).

Moreover, there are three aspects of the aerodynamic behaviour which could be investigated to improve the understanding of the attitude dynamics, and therefore improve re-entry predictions. These are:

- The effect of resonances between aerodynamic motion and orbital motion which can result in increased amplitude of attitude dynamics. This will affect the drag coefficient and thus the re-entry time.
- The determination of whether there are conditions where an object can align before the final two days of re-entry, or remain in a gravity-gradient aligned attitude. This will result in re-entry with a significant period of non-tumbling motion, where the errors may become large if there is a subsequent transition to a tumbling dynamic.
- The effect on the re-entry time of the aerodynamic alignment of an object in the last 48 hours, and whether a general set of rules can be derived such that this effect can be predicted to some extent with limited knowledge of the object’s properties.

The last point is particularly pertinent to the improvement of re-entry prediction. It could be combined with aspects from the first point, and an improved uncertainty analysis, to provide a weighting of the effect of the alignment on the re-entry time where knowledge of the vehicle properties are available. This has the potential to improve the re-entry forecasting over the final 24-48 hours, where some of the largest difficulties lie.

The attitude dynamics can play an important role in the UP for uncontrolled objects and this was also confirmed by UQ analyses on a cylinder case. For the expected range of uncertainties, uncertainties on initial state play a secondary role with respect to the uncertainties in the dynamical environment, such as the atmospheric density.

The re-entry time PDFs cannot be considered uniform. They are, or can be reasonably approximated by skewed normal PDFs, with the consequence that work and time should be spent to answer the question “which part of the tails can be neglected to have reasonable characterisation of the re-entry time window without being too conservative?”, and give general guidelines. Uncertainties on initial attitude and initial attitude rates still need to be properly quantified.

Further, short-term activities that could improve the UQ assessment include:

- a better characterisation of the effects of geomagnetic storms on the re-entry location;
- a different treatment/approximation of the UP output data to reliably catch the main features of PDF's when uncontrolled 6DOF cases are considered;
- the use of the Chebyshev basis rather than the monomials for the treatment of the empirical accelerations, in order to improve the numerical behavior of the method.

Other, longer-term, further work could include:

- the verification that the approaches used to model the main atmospheric and shape sources of uncertainty is sufficient: this would require to model the uncertainties as non-linear function of time and/or altitude, as well as consider different atmospheric models and data;
- the use of appropriate meta-modeling techniques to directly map a range of initial and model uncertainties into re-entry time windows distributions, bringing to a very fast characterisation of the output PDF not requiring any propagation at all.

4 Reference Documents

Table 1 - Attached documents

Ref.	Code	Title	Author	Date
[ATC01]	EXPRO+-GOCE-TN-BRL-001-1-0 (PR00020-D05)	Aerodynamics Analysis and Atmospheric Interaction of GOCE Vehicle	Beck J. and Holbrough I.	2016
[ATC02]	EXPRO+-GOCE-TN-SDS-001-1-1	High Accuracy Orbit Determination - Technical Note 001	Cicalò S. and Guerra F.	2016
[ATC03]	EXPRO+-GOCE-TN-BRL-002-1-0 (PR00020/D12)	BENCHMARKING RE-ENTRY UNCERTAINTIES: RIGID BODY RE-ENTRY DYNAMICS	Holbrough I. and Beck J.	2016
[ATC04]	EXPRO+-GOCE-TN-UOS-001-1-0	Re-Entry Prediction Uncertainty Analysis - Technical Note 002	Minisci E., Serra R.	2016
[ATC05]	EXPRO+-GOCE-TN-SDS-002-1-1	Radar-based Orbit Determination for Re-Entry Predictions - Technical Note 002	Cicalò S.	2016
[ATC06]	EXPRO+-GOCE-FR-1-0	Final Report	Cicalò S., Beck J., Minisci E.	2016

Table 2 - Applicable documents

Ref.	Code	Title	Author	Date
[AD01]	GO-TN-HPF-GS-0111	GOCE Standards	T. Gruber, et al	2014
[AD02]	GOCE-GSEG-EOPG-TN-06-0137	GOCE L1b Products User Handbook	SERCO/DATAMAT Consortium	2006
[AD03]	GO-MA-HPF-GS-0110	GOCE Level 2 Product Data Handbook	The European GOCE Gravity Consortium	2014
[AD04]	XGCE-GSEG-EOPG-TN-09-0007	Note on GOCE instruments Positioning	A. Bigazzi, B. Frommknecht	2010
[AD05]	GSP-REN-SOW-00138 -HSO-GR	Statement of Work ESA EXPRO+ Benchmarking re-entry prediction uncertainties	ESA	2015
[AD06]	IAC-12.A6.2.17	Supporting Conjunction event assessment by acquiring tracking data	Bastida Virgili B. et al	2012

Table 3 - Reference documents

Ref.	Title	Author	Date
[RD01]	GOCE: precise orbit determination for the entire mission http://rd.springer.com/article/10.1007%2Fs00190-014-0742-8	H. Bock, et al	2014
[RD02]	Precise Orbit Determination of the GOCE re-entry phase	F. Gini, et al	2014

Ref.	Title	Author	Date
[RD03]	GOCE Resources, https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/goce	ESA	2015
[RD04]	Calibration of Radar Based Re-Entry Predictions, Proc. 5th International GOCE User Workshop, Paris, France	Lemmens S., et al	2014
[RD05]	GOCE Re-Entry Campaign, Proc. 5th International GOCE User Workshop, Paris, France	Bastida Virgili B., et al	2014
[RD06]	Pseudo-stochastic orbit modeling technique for low Earth orbiters Journal of Geodesy, 80 (1) (2006), pp. 47–60	A Jäggi, U Hugentobler, G Beutler	2006
[RD07]	GOCE Re-Entry Predictions for the Italian Civil Protection Authorities, Proc. 5th International GOCE User Workshop, Paris, France	Pardini C., Anselmo L.	2014
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