PREGO
Benchmarking for Re-entry Prediction

Final Report

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1. INTRODUCTION TO THE STUDY OBJECTIVES AND TASKS

The objective of ESA PREGO activity (ESA/ESOC contract 4000115173/15/F/MOS) is to improve the capacities on re-entry prediction thanks to a complete analysis of the outstanding data set related to the GOCE re-entry occurred in October/November 2013.

From the available GOCE data set composed of: GOCE level 1b dataset for orbit and attitude precise determination (GPS and Quaternion data) and special data set; TIRA radar observations (range, range-rate, azimuth, and elevation measurements), GOCE satellite 3D model and thermodynamic features and GOCE TLE data along the re-entry phase, three interrelated tasks are undertaken.

First task regards to high accuracy orbit determination of the GOCE orbit along the re-entry period. Reduced-dynamic and kinematic orbit estimation has been applied for this task, where:

- **Kinematic orbit**: This is a collection of three dimensional satellite positions at discrete measurement epochs in the Earth-fixed frame. The positions are purely geometric solutions of a kinematic positioning and are thus fully independent of any force models which govern the motion of the Low Earth Orbiter (LEO). A kinematic orbit does not yield information on the satellite positions between the measurement epochs nor on the satellite velocity.
- **Reduced-dynamic orbit**: This orbit satisfies the satellite's equation of motion which is defined by the force models. But the strength of the force models is, to some extent, reduced by introducing pseudo-stochastic orbit parameters, which are, here, piecewise-constant accelerations. These parameters are unphysical but are a very efficient tool to absorb any un- or mismodeled accelerations acting on the satellite (like, e.g., air drag or solar radiation pressure).

In order to ensure high accuracy, several Precise Orbit Determination techniques were applied in order to select the most appropriate one. As the atmospheric density is one of the main aspects playing a role in the capability of determining the re-entry time and location, it has been accurately modelled the effects of the environmental aspects, by evaluation of the main thermosphere models and their input parameters.

Once the reference data is available, in particular the accurate re-entry orbit, the derived information from the first task has been used for

- A **dynamic model analysis**, which provides a re-entry time error budget allocation with respect to uncertainties on the most relevant dynamic parameters. This is done by a sensitivity analysis that takes into account all the inter-relationships between the different variables playing a role in an objects orbit. The sensitive analysis focuses on the GOCE orbit. Among the different parameters or issues considered, the uncertainty impact on re-entry date estimation has been evaluated in terms of orbit estimation, the drag coefficient, and space weather considerations, among them, the occurrence of some special events, but also the effect of the lack of knowledge of space weather. A comparison between the estimated and observed solar activity is done, with analysis on the re-entry estimation capability. In addition to the parametric and Monte-Carlo analysis, two different derivative-free optimisation (DFO) algorithms (such as Bound Optimisation BY Quadratic Approximation -BOBYQA- and Nelder-Mead) have been used in a novel way to determine the orbit of GOCE at various times prior to its re-entry. The objective of the task was to determine if such algorithms could be utilised and be an improvement on traditional Least Square optimisation that is commonly used in orbit determination.
- An **observation model analysis** on the basis of simulated and real observations. Regarding real observations, the Tracking and Imaging Radar (TIRA) radar tracks obtained during GOCE re-entry are compared with the derived reference. This comparison is done in terms of observations (comparing the real observations with the theoretical ones) and in terms of estimated orbit concerning simulated observations, different architectures are simulated to evaluate the re-entry estimation capability.

A final task has also been executed in order to exploit the results and conclusions obtained from dynamic and observational model analysis in terms of re-entry uncertainties models to space objects with aerodynamics characteristics similar to GOCE; i.e. elongated rigid bodies like rocket stages, platforms or payloads. A sensitivity analysis of the aerodynamics and flying qualities to the object dimensions has been carried out to identify the conditions that guarantee a stable flight at high altitude. The main assumptions are:

- Simple short to elongated shape objects, i.e. box and cylinder, have been considered. The results for these shapes have been also compared with GOCE.
- Free Molecular Flow, rarefied and continuum aerodynamics have been computed and analysed.
- Trim, longitudinal and lateral-directional static stability indicators have been estimated and analysed. In particular, for each flight condition, object shape and size, a map function of the centre of gravity position (X-Z) is generated. A symmetric condition in the third axis (Y) is assumed.

This work results in the identification of a range for the variability of the dimension ratio between 2 and 5. This range guarantees on one side good stability properties and on the other enough drag coefficient variability depending on the attitude.

1.1. Applicable Documents

Table 1 specifies the applicable documents that are applicable to the project.

Table 1: Applicable documents

Ref.	Reference	Title	Author	Date
[AD1]	GO-TN-HPF-GS-0111	GOCE Standards	T. Gruber, et al	2014
[AD2]	GOCE-GSEG-EOPG-TN-06-0137	GOCE L1b Products User Handbook	SERCO/DATAMAT Consortium	2006
[AD3]	GO-MA-HPF-GS-0110	GOCE Level 2 Product Data Handbook	The European GOCE Gravity Consortium	2014
[AD4]	XGCE-GSEG-EOPG-TN-09-0007	Note on GOCE instruments Positioning	A. Bigazzi, B. Frommknecht	2010
[AD5]	IAC-12.A6.2.17	Supporting Conjunction event assessment by acquiring tracking data	B. Bastida Virgili, et al	2012

1.2. Acronyms and Abbreviations

The acronyms and abbreviations used in this document are as follows:

Acronym	Description
AD	Applicable Document
AS4	Advanced Space Surveillance System Simulator
BOBYQA	Bound Optimisation By Quadratic Approximation
Cd	Coefficient of Drag
Cr	Coefficient of Reflection
DFO	Derivative Free Optimisation
EGM	Earth Gravitational Model
ESA	European Space Agency
ESOC	European Space Operations Centre
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System

Acronym	Description
KS	Kolmogorov-Smirnov
LEO	Low-Earth Orbit
LS	Least Squares
MASTER	Meteoroid and Space Debris Terrestrial Environment Reference
N/A	Not Applicable
NEWUOA	NEW Unconstrained Optimisation Algorithm
NOAA	National Oceanic and Atmospheric Administration
NRL-MSISE	Naval Research Laboratory mass spectrometer and incoherent scatter radar
OD	Orbit Determination
QA	Quality Assurance
RCS	Radar Cross Section
RD	Reference Document
RMS	Root mean Square
SFU	Solar Flux Units
SGP4	Simplified General Perturbations Four
SoW	Statement of Work
SRIF	sequential Square Root Information Filter
SRP	Solar Radiation Pressure
TBC	To Be Confirmed
TIRA	Tracking & Imaging Radar
TLE	Two Line Element
WP	Work Package

2. RESULTS OF THE STUDY, CONCLUSIONS

2.1. Conclusions from the High Accuracy Orbit Determination Task

The official GOCE PSO could be reproduced by the most recent version of the Bernese GNSS Software. The recomputed kinematic orbits of the last three weeks of the GOCE mission (days 13/294-13/314) were delivered to CNES for the computation of the GOCE densities in the re-entry phase.

Subsequently, air drag modeling has been implemented with the aim to compute more dynamical orbits. Different macro models, HWM14, and different ways to compute the energy accommodation coefficient were tested via the computation of reduced-dynamic GOCE orbits for the last three weeks of the mission. Modeling air drag noticeably reduced the estimated empirical accelerations, with the largest reduction in the along-track direction, but also the cross-track accelerations decreased. The use of HWM14 was necessary in order to reduce the negative offset in the cross-track accelerations. The differences to the kinematic orbits, the orbit overlaps and the SLR residuals served as validation measures, profiting from the air drag modeling. Using the 36-plate GOCE macro model and HWM14 generally resulted in the best results. This was thus the configuration used for the further computations.

Orbits with higher dynamical stiffness were computed by varying the a priori constraints of the piecewise constant empirical accelerations and using the three atmospheric density models DTM2013, MSISE-00, and JB2008. As JB2008 does not provide partial densities, the arithmetic mean of the DTM2013 and MSIS-00 mean molecular masses along the GOCE orbit for days 13/294-13/314 was used for the computation of the energy accommodation coefficient along with JB2008. Regarding the differences to the kinematic orbits, JB2008 performed at the same level as the other two models, for loose constraints closer to MSISE-00, for tighter constraints closer to DTM2013. Regarding the orbit overlaps and the SLR residuals, JB2008 was the model which performed best.

The three thermosphere models were first evaluated over the entire GOCE Science Mission, i.e. from November 2009 to October 2013, through comparison with the official ESA GOCE density dataset. The densities were scaled to the HASDM densities, as was done in the validation procedure, by a factor of 1.23. Only DTM2013 has assimilated part of the GOCE density dataset (to May 2012) and as a result performs best in the comparison (smallest bias and RMS, highest correlation). JB2008 gave different results over the course of the evaluations, and this was due to three different versions of the proxy datafile. The F10.7 and F30 proxies used by NRLMSISE-00 and DTM2013 never change thanks to a rigorous and proven calibration method. The model evaluation results pertain to a specific local time frame due to the GOCE orbit, which was nearly Sun synchronous in an initially dawn-dusk orbit (and 7:30 am/pm at the end of the mission). Therefore, DTM2013 and NRLMSISE-00 were also compared with CHAMP densities at a higher altitude (330 km on average over 2001-2010), which cover 24-hr local time approximately every 4 months. The comparison revealed that the dawn/dusk local times are modeled slightly less accurate than the rest of the 24-hr day, so GOCE results do not give optimistic model performance statistics. Comparison to Air Force mean densities revealed small, with a few percent amplitude, semidiurnal signals in the O/C, which are otherwise not significantly biased.

The total modeled effect of geomagnetic activity was evaluated by running models with a constant low ap of 4, and comparing to densities obtained when using the observed ap. This total effect can be considered as a worst case forecast scenario, namely low activity predicted in case of enhanced or storm activity, which happens regularly in orbit predictions. At low altitude, geomagnetic perturbations become smaller and smaller, and in the GOCE timeframe maximum perturbations of 60-70% were calculated.

The densities for the last three weeks of GOCE were inferred from the calibrated common mode accelerations. The X-bias remained constant to 30 October, after which it started increasing for unknown reasons. Comparison of the GOCE with HASDM densities revealed that the differences started increasing from that date onward too, and closer inspection showed that the accelerometer measurements are more and more affected by errors due to saturation most probably. Therefore, not all density data can be used for scientific analyses anymore after 30 October.

The orbit computations confirmed the erroneous accelerometer data starting 31 October. Up to that date, the RMS-of-fit to the GOCE kinematic orbit positions are an order of magnitude better than computations with surface models, whereas they become comparable and even worse in the last few days. The estimated drag scale factors for the thermosphere models are in agreement with the calculated O/C in the direct model to density comparisons.

Re-entry calculations are rather short-time scale events that last typically less than 2 weeks. Therefore, model error can be significant due to errors in the *observed* proxies too. In case of the GOCE re-entry, the F30 proxy appears to be the cause for the drift in the O/C ratios – which is not observed in the F10.7 driven NRLMSISE-00.

2.2. Conclusions from the Re-entry Prediction Uncertainties Task

During the work related to the dynamic model analysis, several aspects affecting the dynamic of the re-entry prediction have been analysed.

First the uncertainty in position and velocity impact is investigated, concluding, through Monte Carlo analysis that, as expected, the size of the position and velocity uncertainty directly map to the re-entry prediction error. Velocity errors play a major role in the prediction error.

Consideration of spherical and elliptical covariance matrix does not seem to vary the behaviour. Typical uncertainties derived from radar observations can lead to up 10% of prediction error when propagating about 25 days.

Regarding the impact of space weather modelling, it can be highlighted that the lack of knowledge and predictability of the Space Weather conditions poses a strong influence on the re-entry predictions. Presence of storms is very relevant, although difficult to predict. Current forecast capability of Space Weather is very much limited, observing differences in the two analysed models. Of course, solar cycle impact is relevant, and shall be accounted for any re-entry prediction analysis

In regards to the observational model analysis, the study showed that different approaches for processing measurements for different sensor architectures, accuracy of the data and observational profile.

From the simulation analysis of different observational approaches, it seems that one sensor like TIRA allows predicting the orbit with good accuracy, although some benefits are shown if two observation sites are available. Regarding the accuracy, as expected, the better accuracy of the sensor error improves the results but it seems that TIRA's current accuracy is again enough for predictions.

The duration of tracks and the number of measurements inside a track does not seem as important as gaps between tracks (although they would improve the results). Large gaps between tracks (days) destabilise the filter (SRIF). The length of observing gaps between observing tracks plays a major role in the final achievable accuracy.

Re-entry analysis was performed with measurements from 1, 2 and 3 radars with good results for all of them. For the case of three sensors, the difference between the estimated re-entry and the real one is in the order of seconds and about 60 km in position (near to Falkland Island).

Two DFO algorithms have been used for the particular problem of re-entry computations. For this particular case, BOBQYA algorithm outperformed the Nelder-Mead algorithm (lower RMS position error) in most cases. This is likely to be because BOBQYA is more optimised for such problems as OD. The error in predicted re-entry time is still relatively high even a few days before re-entry. As a result even very good OD practices cannot predict re-entry location and time with any particular certainty.

DFO algorithms are becoming more popular given the increased complexity of functions, which need to be optimised efficiently. Optimisation from orbital propagation is still a topic that requires significant research in order to improve its accuracy. In order to fully understand and determine DFO's true effectiveness more work needs to be done. A lot of other DFO's exist which may be able to be better suited producing less error in less computational time.

2.3. Conclusions from the Rigid Body Dynamics Task

The aerodynamic behaviour at high altitudes of rigid bodies that present commonalities with GOCE has been studied.

The space objects selection process has been based on the analysis of the aerodynamics and flying qualities for simple shapes as short and elongated cylinders and boxes. They are considered well representative respectively of rocket bodies (upper stages) and payloads (cubeSats). Based on the

DISCOS database, 17 space objects have been identified (matching the list of criteria identified) and among them 5 objects have been selected for further analysis.

Globally it is concluded that elongated bodies that can be approximated as simple cylinder and boxes, potentially show stable attitude behaviour during their decay below altitude of 250 km. For such objects, knowing the attitude behaviour significantly reduces the variability in the ballistic coefficient and therefore allows a better estimation of the re-entry time. The attitude performance models extracted from the TLE analysis results aligned with the expected behaviour; however, the approach followed should be extended to a larger number of objects to proper verify its applicability.

A generalization of the aerodynamic stability analysis for different object shapes is not straightforward and requires dedicated analysis. However, the extraction of an attitude performance model from the analysis of the TLE remains a potentially valid approach.

2.4. Summary of error budget

As a summary of the encountered results, Table 2 lists the contributions of individual errors, as quantified in the three work packages summarised above.

Table 2: Sources of errors in the re-entry computation

Item	Error / Uncertainty
GOCE GPS Precise Orbit	3-5 cm
12h extrapolation, GPS state vector	Min/max, RMS of Fig7 left
24h extrapolation, GPS state vector	Min/max, RMS of Fig7 right
24h arc, state vector & 1 drag scale estimated	10-80 m (less than 1%)
Thermosphere model bias variability (1-sigma)	
Time scale: Annual for JB2008&DTM2013 (NRLMSISE-00)	2% (5%)
Monthly	4% (7%)
Daily	6.5% (9.5%)
½ revolution	7-9% (10-11%)
Re-entry uncertainty due to state vector error	**(nominal re-entry = 24.75 days)**
1 km	
0.1 km & 1 m/s (spherical error)	30%
0.1 km & 1 m/s (non-spherical error)	15%
Re-entry variability due to solar cycle phase	**(nominal re-entry = 24.75 days)**
High activity (“max” of cycles)	19.1 ± 3.1 days (16.2%)
Low (less than 75 sfu)	35.2 ± 1.7 days (4.8%)
Ascending phase	28.6 ± 5.1 days (17.8%)
Decaying phase	26.9 ± 5.3 days (19.7%)
Ap=4 (geomagnetic quiet conditions)	Error from 2.8% in low solar activity period up to 15.8% in high solar activity
Re-entry uncertainty due to predicted solar activity	**(nominal re-entry = 24.75 days)**
Forecasted Solar activity	5% in re-entry time
Observational model (network & precision)	

Item	Error / Uncertainty
2 sensors with respect to 1 sensor only / 3 sensors wrt 1 sensor	70% of position error / 36% of position error 69% of re-entry time error 37% of re-entry time error
Rigid body:	
Elongated body with a ratio between the main dimension in the range 3-5	BC_{max}/BC_{min} up to 5 depending on attitude Even higher ratio in case of lateral panels (up to 10 for GOCE)

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