BALLISTIC PARAMETER AND LIFETIME ASSESSMENT FOR CATALOGUED OBJECTS

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1 ABSTRACT

The *LASCO* (Lifetime Assessment of Catalogued Objects) tool is dedicated to the computation of the orbital lifetimes of all catalogued objects. It was developed in the course of an upgrade of ESA's DISCOS database. It consists of a graphical user interface, and four separate modules addressing individual tasks.
A single-point interface to the DISCOS database is realised by means of a Perl script. It extracts data from DISCOS, initiates the execution of the subordinated modules and writes the results to the database.

1. BaPIT (Ballistic Parameter Iteration Tool) calculates the ballistic parameters of catalogued objects contained in DISCOS.
2. SOLAT (Simple Orbital Lifetime Assessment Tool) calculates the orbital lifetime of catalogued objects using different orbit propagation methods depending on the expected lifetime and the required accuracy.
3. RIO (Risk Object Re-entry Warning Tool) performs detailed decay analysis for all objects identified as hazardous, and having an expected lifetime below a pre-defined time span.

The amount and continuity of ballistic parameter and lifetime assessment data provided by LASCO for the DISCOS database is unprecedented. It allows for a global analysis of the currently tracked population. The primary aim of this paper is to give a survey of the capabilities of LASCO. A second aspect will be to provide a first critical review of the results obtained from the LASCO runs performed since the beginning of the operational phase in October 1999.

2 INTRODUCTION

2.1 Overview

Since 1990 ESA is maintaining the DISCOS (Database and Information System Characterising Objects in Space) database. DISCOS contains technical and statistical information on the tracked space objects, as well as launcher and launch-site related information. Orbital data of the catalogued objects – in terms of historic and periodically updated Two Line Elements (TLEs) is also included in DISCOS.

The LASCO software has been developed under the ESA Contract No. 12318/97/D/IM "Upgrade of the DISCOS Database" [1] in order to ensure a sufficiently long pre-warning period for the co-ordination of re-entry monitoring campaigns for risk objects as e.g. COSMOS 954, SALYUT7, MIR and others fulfilling user specified risk criteria.
The following requirements are resulting from this motivation:

- identification of potentially hazardous objects,
- supply lifetime information for as many catalogued objects as possible,
- reasonable CPU consumption and storage requirements,
- adequate accuracy, e.g.
  - long remaining lifetime: moderate accuracy
  - short remaining lifetime: high accuracy

Since the lifetime prediction requires the knowledge of the ballistic parameter (area-to-mass ratio multiplied by the drag coefficient), an additional tool had to be developed to provide the required data.

2.2 Implementation

The LASCO software package is composed of five software tools, which are dedicated to perform the tasks given in Table 1.

Table 1: LASCO tools

tool	purpose
LASCO-0	extraction of data form DISCOS, launch of the subordinated tools, writing of derived data to DISCOS
LASCO-1 BaPIT	ballistic parameter calculation
LASCO-2 SOLAT	orbital lifetime prediction
LASCO-3 RIO	identification of risk objects, and decay prediction
LASCO-4	graphical user interface

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Fig. 1 gives an overview over the task flow of the LASCO package.

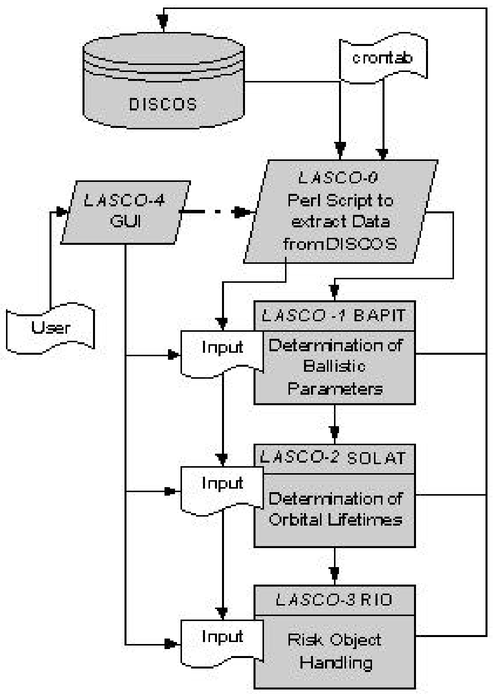

Fig. 1: Process flow of the LASCO tool

After specifying the user input data of all LASCO tools (LASCO-0, BaPIT, SOLAT, and RIO) via the LASCO graphical user interface (GUI), the Perl-script LASCO-0 is launched.
A ballistic parameter update with BaPIT is performed for all objects if no ballistic parameter value is found in DISCOS, or if expected orbital lifetime is less than a certain lifetime threshold (default: 2 years). A second lifetime threshold (default: 2 years) is implemented for the selection of the orbit propagation tool for the ballistic parameter determination procedure: if the expected lifetime is less than the threshold value, FOCUS is selected, other wise ORBPRO (for a brief description of the orbit propagators refer to Table 3).
The following orbital lifetime calculation with SOLAT makes use of the ballistic parameter values written to DISCOS. SOLAT always performs orbital lifetime prediction for all objects. The user may select the orbit propagation tools depending on the expected lifetime, which is read from the database. If no lifetime value is found, a first order lifetime prediction takes place first.
The last step of the LASCO run is the identification of potentially hazardous objects (e.g. with large mass or nuclear power sources on board) with RIO. For each of these objects, which are identified according to user selectable parameters, a detailed re-entry determination is performed.
A complete LASCO run including ballistic parameter and lifetime prediction for all 8400 objects contained in DISCOS requires approximately 48 hours on the ESOC target computer (SUN workstation). If the data provided by LASCO is updated on a regular basis (e.g. every three months) this time will be reduced significantly, because not all ballistic parameters need to be re-calculated.

3 BALLISTIC PARAMETER DETERMINATION

3.1 Implementation

The implementation logic is given in Table 2. Case 1 to 3 are ordered and processed hierarchically.

Table 2: Ballistic parameter determination logic

case	description
1	average cross sectional area and mass available from DISCOS table ALL_OBJECTS; use data for ballistic parameter calculation
2	use ballistic parameter determined by *BaPIT* if the quality criteria are fulfilled (standard deviation less than 15%)
3	use the default value of the ballistic parameter (0.011 kg/m^2)

No ballistic parameter calculation with BaPIT is required, if the mass and cross-sectional area values are found in DISCOS. In case 1 the ballistic parameter is given by

$$B = c_D * A/m \qquad (1)$$

where $c_D = 2.2$ is assumed.

If case 1 is not applicable (no data in DISCOS), the ballistic parameter determination is performed by means of BaPIT. BaPIT makes use of a so called “shooting method”, which is applied to a number of subsequent pairs of TLE sets as available from DISCOS.

3.2 Shooting Method

The shooting method is an iterative process of estimating the ballistic parameter of a given object by evaluating its orbital evolution over a given time span Δt, i.e. from a start epoch T_0 to a destination epoch $T_0 + \Delta t$. Starting from a given set of orbital elements $(a, e, i)_{T_0}$, the method applies orbit propagation tools and an assumption of the objects ballistic parameter to propagate the orbit over the time span Δt. Based on the difference between the propagated and measured orbit at $T_0 + \Delta t$ the method iteratively changes the ballistic parameter until a (user-specified) accuracy criterion is reached. The method applied in LASCO is further described in [4]. The method requires a minimum semi-major axis decrease. Thus, BaPIT can be applied to objects with perigee altitudes below 1000 km only. Otherwise, the ballistic parameter is set to the default value of currently $0.011 m^2/kg$. For each object the average value of all determined ballistic parameters (one for each TLE pair) is written to the database, if the standard deviation is less than a pre-defined threshold (e.g. 15%). If the quality requirement is not reached, the default value is written to DISCOS (case 3).

The ballistic parameter determination was validated by a comparison of the ballistic parameters calculated with each of the orbit propagators for some objects with well known geometry and mass (e.g. ODERACS spheres). This comparison was also performed for various objects on different orbits, e.g.

- NOAA 14, sun-synchronous orbit,
- MIR, low Earth orbit,
- ARIANE rocket body, GEO transfer orbit.

In all cases the correspondence of the results was very good [1].

3.3 Results

The ballistic parameter distributions derived from the LASCO runs performed in March 2000 and in August 2000 are shown in Fig. 2.

It must be mentioned here, that for the first run geometry and mass data from DISCOS were not available. Consequently, all 6583 ballistic parameters were calculated by BaPIT. A second difference between the LASCO runs is the maximum perigee altitude for BaPIT: it has been changed from 2000km (March 2000) to 1000km (August 2000).

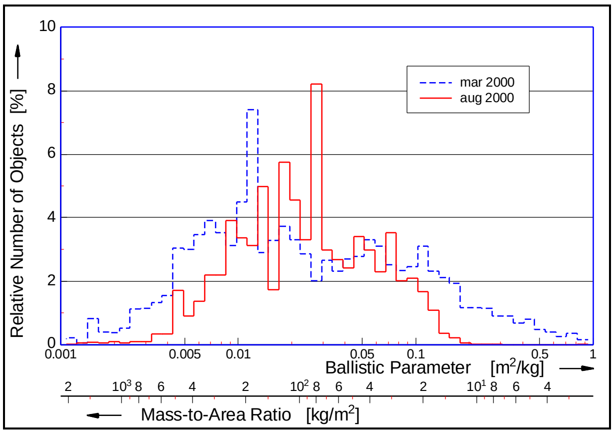

Fig. 2: Ballistic parameter distributions of two LASCO runs (objects with default B are not included)

These changes result in significantly different distributions. The first run yields more very small and very large ballistic parameters. This may be explained by larger uncertainties in the ballistic parameter distribution for objects with perigees between 1000km and 2000km altitude. Generally, a shift from small ballistic parameters to larger ones can be observed on the left-hand side of the diagram. This may be a consequence of the consideration of cross-sectional area and mass data in case of the large number of 3597 objects (for comparison: BaPIT provided ballistic parameter data for 2814 objects in this LASCO run.) the comparison presented in section 3.4 in connection with the re-entry prediction results (section 4.2) indicate.

3.4 Comparison to other Sources

The comparison of the ballistic parameter data calculated with BaPIT is performed on the basis of data provided by CERT-ONERA on one hand, and on data provided in the DISCOS database one the other hand.

For comparison purposes the ballistic parameter ratio was calculated by dividing the BaPIT value by the value extracted from the literature (Jane's Space Directory 1996 and 1997, Kramer's 1996) or from DISCOS, respectively, for each object where these data were available.

The distributions of the ballistic parameter ratios (BPR) is given in Fig. 3. An exact agreement of the data provided by BaPIT and the data from other sources would be reflected by a ratio of BPR=1. BPR < 1 means that the values determined by BaPIT are smaller than those from other sources, BPR > 1 means they are larger. The remarkable result of this comparison is, that BaPIT calculates smaller ballistic parameters in most cases, where the most probable BPR is about 0.5.

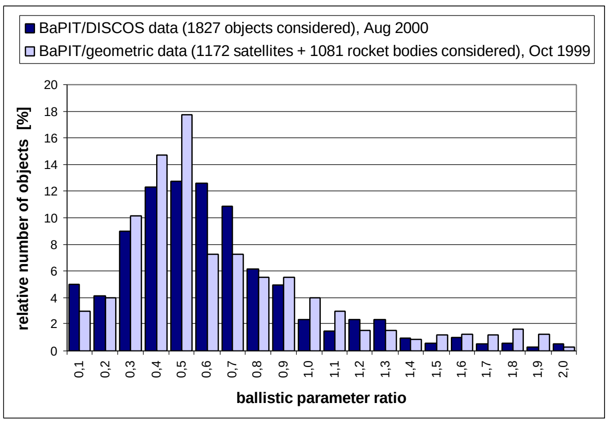

Fig. 3: Comparison of ballistic parameters calculated with BaPIT and ballistic parameters calculated from object geometry and mass

Possible reasons for this behaviour are listed as follows:

The most probable reason for this behaviour is a bias (i.e. an error that applies to all objects) in either the results determined by BaPIT or the results derived from geometric considerations. For BaPIT such a bias could be introduced by inaccurate orbit predictions, which could be caused by inaccurate or outdated solar activity values for the orbit propagation performed in BaPIT.

A bias in the data computed from the object geometry could be introduced by inappropriate mass values (e.g. the empty mass of an upper stage is used, although some fuel is left in the stage), or inappropriate cross sectional area determination due to an unknown attitude of the object (note that the cross sectional area averaged over time is needed for the ballistic parameter determination).

Manoeuvring of several objects would lead to completely inexact semi-major axis gradients, and thus to incorrect ballistic parameters. Geometry and mass is known for satellites and upper stages/rocket bodies only, but not for fragments from spacecraft break-ups which make up the majority of the catalogued objects. Since objects with known geometry and mass may be considered in the comparison only, it must be assumed that a significant part (e.g. 20%) of these objects is manoeuvred.

4 ORBITAL LIFETIME ASSESSMENT

4.1 Implementation

Lifetime assessment is performed by means of orbit propagation tools, which are applied to each object. A user-defined criterion (e.g. perigee altitude below 130 km) specifying 'end-of-life' (EOL) is checked to determine the EOL date. The tools used for this purpose are described in Table 3.

Table 3: Lifetime determination tools

tool	method	description
FOCUS	propagation of mean orbital elements by numerical integration of the averaged perturbation equations	fast lifetime calculation; considers: zonal harmonics of the geo-potential, air-drag in an oblate, diurnal atmosphere, luni-solar perturbations, solar radiation pressure [2]
ORPPRO	analytical orbit propagation based on the theory of King-Hele [3]	very fast lifetime calculation; variation of solar activity, and atmospheric density at perigee considered, CIRA 72 atmosphere model,
FLiP	computation of King-Hele's straight forward orbital lifetime equations [3]	extremely fast lifetime calculation; air-drag perturbation only (based on the atmospheric density at initial perigee), spherical exponential atmosphere, constant mean solar activity,

An initial lifetime estimation is done for each new object added to the database using simple analytic orbital lifetime equations implemented in the FLiP software.
For the following lifetime calculations, which must account for sufficient accuracy and computation efficiency as well, two orbit propagators are available. They are selected automatically for each object due to the lifetime entry in DISCOS under consideration of a user-defined lifetime-class/orbit propagator assignment. For very long expected lifetimes the results of FLiP serve as a first order lifetime estimate. Table 4 gives an example of a possible assignment of the lifetime estimation tools to different lifetime classes.

Table 4: Selection of orbit propagation method

expected lifetime		orbit propagator
short	< 20 years	FOCUS
medium & long	< 1000 years	ORBPRO
very long	> 1000 years	FLiP

The lifetime prediction considers the latest available orbital elements set, and the ballistic coefficient determined before.
The object's perigee altitude must be less than 5000 km, otherwise the orbital lifetime is set to a default value of 10^7 years.
The lifetimes of all objects have been calculated with each applicable orbit propagator/lifetime assessment tool in order to verify the results. For these comparison the same ballistic parameter, and the same orbital element data set was used for each object.
The orbital lifetime values of FLiP are plotted against those of ORBPRO (thin), and those of FOCUS against the FLiP values as given in Fig. 4. The diagonal line then depicts exact agreement of the values.
It can be stated, that the correspondence of the calculated lifetimes is good for lifetimes greater than approximately 10 years (corresponding to one solar cycle). For shorter lifetimes deviations between FLiP and FOCUS/ORBPRO are observed which is a consequence of the consideration of the solar activity at the orbit propagation start epoch.

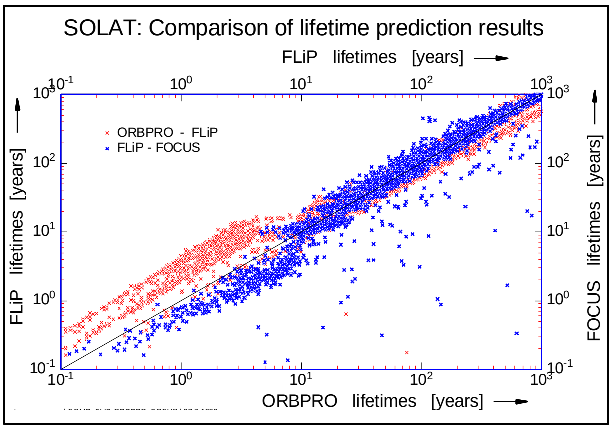

Fig. 4: Comparison of orbital lifetime values of the different prediction tools

In case of eccentric orbits the results of FOCUS may differ a lot from those of the other tools, since FOCUS considers 3rd body perturbations (Sun, Moon) which may lead to (much) shorter or longer lifetimes, respectively.

4.2 Results

Fig. 5 shows the lifetime distributions of the catalogued objects as calculated by SOLAT in March 2000 and August 2000. It was mentioned before that between these two LASCO runs some changes in the ballistic parameter determination took place. An additional change which has no influence on the discussion of the ballistic parameter calculation, may however have an impact on the orbital lifetime distribution: The default value of the ballistic parameter for the first run was $0.04 m^2/kg$, while for the second run $0.011 m^2/kg$ was used. The number of objects with default B is 1738 for the first, and 1968 for the second run.

Some distinct lifetime classes can be identified from Fig. 5. An assignment of these lifetime classes to certain groups of spacecraft is problematic, since different types of objects on different orbits may have similar lifetimes.

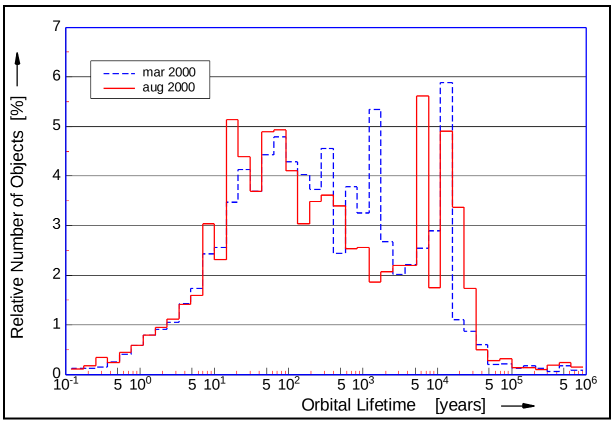

Fig. 5: Orbital lifetime distributions of two LASCO runs

In order to obtain a first insight to the quality of the lifetime prediction, the predicted re-entry dates are compared to the observed re-entry dates. All objects which were decayed since the LASCO run performed in August 2000 until march 2001 are considered in this comparison.

The observed re-entry date is plotted against the predicted re-entry date for each of the 194 decayed object in Fig. 6. It is distinguished between the method used for the determination of the ballistic parameter. The solid line indicates exact correspondence between observed and predicted decay date.

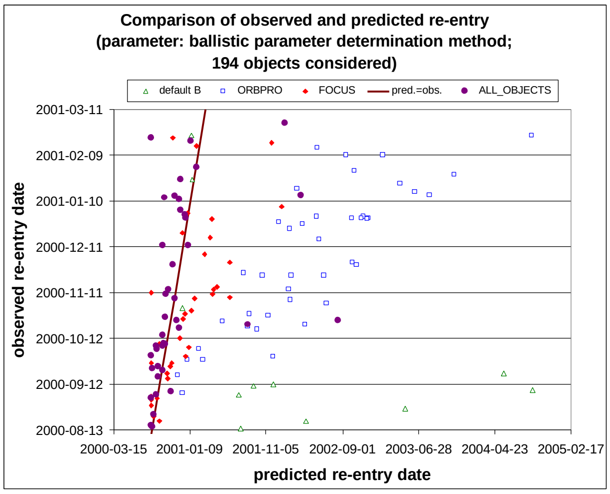

Fig. 6: Comparison of observed and predicted re-entry date (lifetime prediction performed in August 2000)

82% of the re-entry dates were calculated with FOCUS due to the very short expected lifetime of the objects included in this investigation. Thus, the influence of different orbit propagation methods in the lifetime prediction is nearly excluded.

Fig. 6 shows that distinct sectors of the diagram are occupied by the different types of ballistic parameters. The best results are obtained with the ballistic parameters calculated from spacecraft data, followed by those calculated with FOCUS. The lifetime prediction with ballistic parameters determined with ORBPRO leads to prediction errors in the order of factor 4. The worst correspondence of observed and predicted decay date is obtained if the ballistic parameter default value is used for lifetime prediction (here: $0.011 m^2/kg$). In most cases this value is much to small as indicated by a lifetime overestimation of about factor 10. A larger default value should yield better results in most cases.

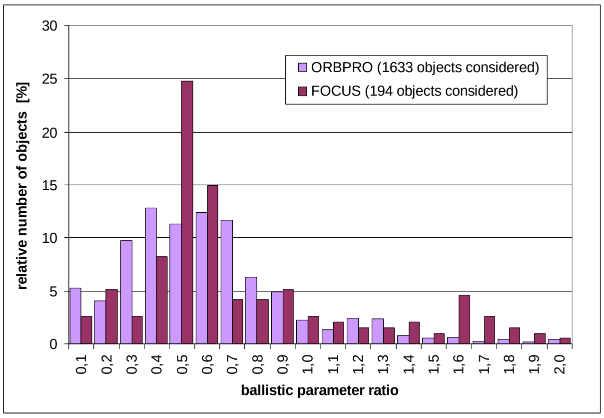

Fig. 7: Comparison of ballistic parameters calculated with BaPIT and ballistic parameters calculated from object geometry and mass

Although the deviations of the ballistic parameter values calculated by FOCUS and ORBPRO show the same behaviour (s Fig. 7, which is based on the same data as Fig. 3, but distinguishes between the orbit propagation method used in BaPIT), it seems that FOCUS yields better lifetime results if the ballistic parameter was also calculated by FOCUS.

5 SUMMARY AND CONCLUSION

The results of the ballistic parameter and lifetime assessment as presented in this paper may be summarised as follows:
LASCO provides ballistic parameter information for 88% of 8370 catalogued objects.
The ballistic parameters calculated with BaPIT differ from those calculated from the object geometry and mass in most cases.
LASCO provides lifetime information for 77% of the catalogued objects.
The predicted lifetimes show deviations from the observed lifetimes in the very short orbital lifetime regime. The magnitude of these deviations is strongly depending on the orbit propagation method used in the ballistic parameter determination.
The ballistic parameter default value should be enlarged in order to obtain better lifetime estimates.

Generally, an evaluation of the LASCO package is not possible on the basis of the very small number (compared to the total number of catalogued objects of currently 8370) of 194 objects. Nevertheless, the comparison of predicted and observed re-entry indicates differences which need further clarification.

The following evaluation matrix gives a rough evaluation of the orbit propagators/lifetime estimation tools used in the LASCO sub-packages.

	FOCUS	ORBPRO	FLiP
BaPIT	good	not recommendable	n/a
SOLAT	very good	good for large expected lifetimes	should be used for very large expected lifetimes only
RIO	very good	n/a	n/a

An update of the LASCO software on the basis of further investigations of the available data seems to be recommendable. Such an update should include an identification and processing of manoeuvred objects.

6 REFERENCES

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