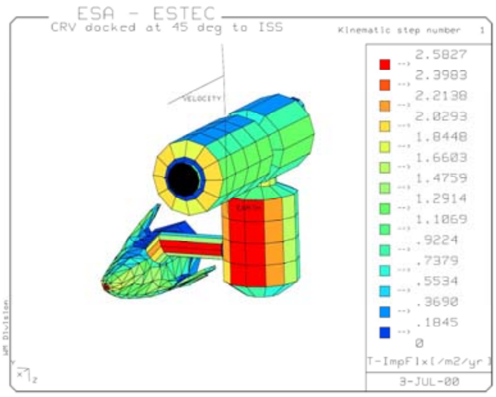
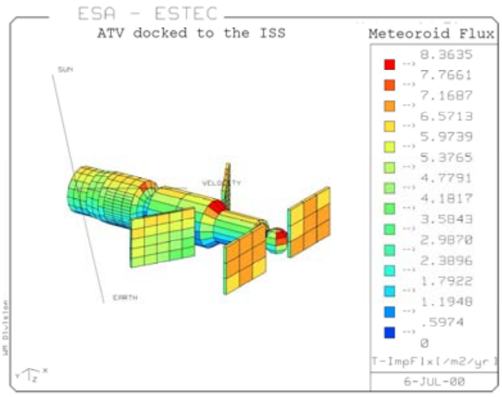
Upgrade of ESABASE/Debris

Executive Summary Report





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1 Document Information

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III. List of References

/1/ ESABASE/DEBRIS, Release 3, ***Software User Manual***, eta_max space ref. R033_r020_SUM, Version 1.0, 09/2002

/2/ ESABASE/DEBRIS, Release 3, ***User Requirements Document***, eta_max space ref. R033_r018_URD, Version 1.0, 03/2002

/3/ ESABASE/DEBRIS, Release 3, ***Software Specification Document***, eta_max space ref. R033_SSD, Version 0.9, 03/2002

/4/ ESABASE/DEBRIS, Release 3, ***Software Verification and Validation Plan***, eta_max space ref. R033_r019_SVVP, Version 1.05, 09/2002

/5/ ESABASE/DEBRIS, Release 3, ***Technical Description***, eta_max space ref. R033_r025_TD, Version 1.0, 11/2002

/6/ Upgrade of ESABASE/DEBRIS, Study Note of WP 1 (Review of Models and Tools), eta_max space ref. R033_t016, Version 0.9, 11/2001

/7/ ESABASE/DEBRIS, Release 2, Software User Manual, HTS ref. S-50/95-SUM-HTS, August 11, 1998

/8/ Divine, N. “Five Populations of Interplanetary Meteoroids” , Journal Geophysical Research 98, 17,029- 17,048 1993.

/9/ Divine, Gruen, Staubach, ‘Modelling the Meteoroids Distribution in Interplanetary Space and Earth’, Proceedings on the first European Conference on Space Debris, Darm-stadt/Germany, 5-7 April 1993, ESA SD-01, p.245-250

/10/ H. Sdunnus, G. Drolshagen, C. Lemcke, "Enhanced Meteoroid/Debris 3-D Analysis Tool", paper held at the 2nd European Conference on Space Debris, ESOC, Darmstadt, 1997

/11/ M. Rival and J.C. Mandeville, ‘Modelling of Ejecta produced upon Hypervelocity Impacts’, Space Debris, Vol.1, pp. 45-57, 1999

/12/ P. Wegener, J. Bendisch, K.D. Bunte, H. Sdunnus; Upgrade of the ESA MASTER Model; Final Report of ESOC/TOS-GMA contract 12318/97/D/IM; May 2000

/13/ H. Klinkrad, J. Bendisch, K.D. Bunte, H. Krag, H. Sdunnus, P. Wegener; The MASTER-99 Space Debris and Meteoroid Environment Model, COSPAR 2000 Conference, Warsaw, 16.-23. July 2000

/14/ Bendisch, J.; Klinkrad, H.; Li, X.; Sdunnus, H.; Wegener, P.; Wiedemann, C.; Rex, D.; Results of the Upgraded MASTER model 50th IAF congress, paper IAA-99-IAA.6.6.02, Amsterdam, The Netherlands, 10/99

/15/ Bendisch, J., K. D. Bunte, S. Hauptmann, H. Krag, R. Walker, P. Wegener, C. Wiedemann; Upgrade of the ESA MASTER Space Debris and Meteoroid Environment Model – Final Report, ESA/ESOC Contract 14710/00/D/HK, Sep 2002

IV. List of Abbreviations

Abbreviation	Description
ATV	automated transfer vehicle
ESA	European Space Agency
ESTEC	European Space Research and Technology Centre
GEO	geostationary orbit
GTO	geostationary transfer orbit
ISS	international space station
LDEF	long duration exposure facility
LEO	low Earth orbit
MASTER	meteoroid and space debris terrestrial environment reference model
MIDAS	Missile Defense Alarm System
NaK	Sodium-Potassium
NASA	National Astronautics and Space Administration
ORDEM	orbital debris environment model
RORSAT	radar ocean reconnaissance satellite
SRM	solid rocket motor
SSD	software specification document
SUM	software user manual
SVVP	software validation and verification plan
TLE	two line elements
TD	technical description
URD	user requirements document
WP	work package

V. Distribution List

Company	Name	Comment
ESTEC/TOS-EMA	Dr. G. Drolshagen	as pdf per Email
Study Team	all	Via PWE

VI. List of Figures

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2 Introduction

2.1 Scope of the Study

ESABASE/DEBRIS is a part of the 3-D numerical analysis tool ESABASE. The DEBRIS application (see /1/ to /6/, /10/), has been developed and upgraded under a former ESTEC Contracts to analyse meteoroid and debris impacts and to assess the resulting damage. The availability of accurate debris and meteoroid flux models and up-to-date impact risk assessment tools are crucial for preparing and designing manned and unmanned space missions. ESABASE is widely used within Europe and has successfully been applied to numerous missions. In recent years, the knowledge on the meteoroid and space debris environment has improved, new flux models have been developed and new user requirements for impact risk assessment capabilities have been identified. The goal of this study was to take into account those recent developments. The main tasks to be performed during the ESABASE/DEBRIS upgrade thus were

- to review the existing ESABASE/DEBRIS tool, its framework, user interface and data structure,
- to review and implement the following tools:
  - the MASTER 2001 Standard application,
  - the Divine-Staubach meteoroid model,
  - an improved ejecta model,
- to add enhancements to the user interface and to the format of the input/output files,
- to validate the added modules, the existing documentation, and the user interface,
- to document the software engineering activities of this project.

The implementation of these state-of-the-art debris and meteoroid models adds the following advantages to the ESABASE/DEBRIS application:

- In contrast to former releases, ESABASE is now able to provide debris flux and damage analysis for the complete altitude range from LEO to GEO.

- In contrast to former releases, ESABASE is now able to provide flux and damage analysis for any target orbit, e.g. highly eccentric orbits (GTO).
  - Due to the implementation of the MASTER Standard application, it is now possible to select and de-select single debris population sources. This allows an analysis of the specific behaviour of single sources.

- The MASTER Standard application also includes realistic population snapshots for historic and future epochs, allowing e.g the
  - analysis of the historic LDEF mission
  - analysis of the future risk for ISS modules, etc.

2.2 Work Packages

The tasks of the contract were broken down into eight major work packages :

- WP 1 Review of Tools and Models
- WP 2 Implementation of the MASTER debris Model
- WP 3 Implementation of the Divine-Staubach Model
- WP 4 Other Enhancements
- WP 5 Implementation into the new ESABASE/DEBRIS User Interface
- WP 6 Tool Validation
- WP 7 Documentation
- WP 8 Management

The work breakdown structure is basically oriented towards the application of ESA's PSS-05 software engineering standards applied for this study. WP 1 represents the user requirements acquisition phase, while WPs 2 and 3 involved the architectural and detailed design development of the software to be developed.

Work package 4 covered an update of the ejecta model and additional enhancements to the user interface and input/output format of the ESABASE/DEBRIS tool.

Work package 5 involved the implementation of the developed software into the ESABASE user interface, ensuring the availability of all necessary functions and the correct operation of the tool. The upgraded version of ESABASE/DEBRIS was also installed at ESA/ESTEC in the course of this WP.

Software integration and validation was subject to WP 6. WP 7 involved the production of all required documentation while management aspects were covered by WP 8.

3 The ESABASE/DEBRIS Tool

3.1.1 Overview

ESABASE/DEBRIS is a unique tool to perform numerical impact analysis and risk assessment for orbiting spacecraft under consideration of their orbital evolution and attitude. It allows to predict the number of impacts from meteoroids and space debris and the resulting damage under consideration of realistic shielding and material characteristics. The DEBRIS application is embedded in the ESABASE software.

The ESABASE tool enables the user to construct a 3-dimensional analysis model and to perform a variety of space–specific analyses on this model along its orbital trajectory. The analysis model constructed with ESABASE incorporates the geometry of the system and other relevant data such as surface and material properties. Other commonly required data such as orbital position and attitude may also be generated in standard formats for the analysis. This data can then be used as input for any of the applications accessible from ESABASE. This simplifies the realisation of different engineering analyses and reduces the possibility of inconsistencies

Apart from the DEBRIS tool, ESABASE includes a number of different applications:

- Atomic oxygen recession analysis.
- Spacecraft charging analysis.
- Field of view analysis (qualitative and quantitative).
- Mass related-analyses (budgets, system properties, static and dynamic balancing, mass sensitivity).
- Outgassing contamination analysis.
- Plume-impingement effects analysis (forces, torque, heat flux).
- Space environment perturbation analysis (aerodynamic drag, gravity gradient, magnetic torques, solar radiation pressure).
- Space radiation environment prediction and protective shielding analysis.
- Electromagnetic sun radiation exposure assessment.
- Telecommunication related analyses (visibility contours, link occultation).
- Thermal analysis modelling, pre/post processing.

Not all of these modules are frequently applied to space missions. The DEBRIS application upgraded in this contract, however, is one of the frequently used parts of ESABASE. ESABASE/DEBRIS calculates the meteoroids and debris fluxes for a given orbit and computes the damage on all exposed surfaces taking into account a variety of flux models, damage equations and shielding design. The value of the ESABASE/DEBRIS application largely depends on the quality and actuality of the implemented flux and damage models.

3.1.2 The ESABASE Architecture

ESABASE consists of a so called "framework" which is used to generate the model geometry and properties. It also includes an orbit propagator, facilities for automatic pointing of the objects of the spacecraft model, environmental models (e.g. atmosphere model, radiation model, etc.), and graphic tools to display the spacecraft model, its properties, and the results of the various applications which may be launched by the graphical user interface which is part of the framework.

ESABASE/DEBRIS is one application within the ESABASE tool, and makes use of parts of the ESABASE framework as e.g. the description of the spacecraft geometry model, orientation/kinematics, and orbit. The DEBRIS application analyses the interaction of the model with the meteoroids and debris environment. The analysis can be performed using various models for space debris and meteoroids. A ray-tracing method is used to analyse the direction of the particles and the impact distributions over the geometry. Then, by using given damage equations and shielding data, the tool calculates the number of penetrations. Additional damage calculations like crater size and damage from secondary impact ejecta are also possible.

The ESABASE/DEBRIS software provided is composed of 266 source files, the majority of them corresponding to the maink3 executable, which is the main analyse executable. The software is written in standard FORTRAN 77 (except for the ray-tracing library routines, which are written in C), and is embedded in the ESABASE structure as shown in Figure 1.

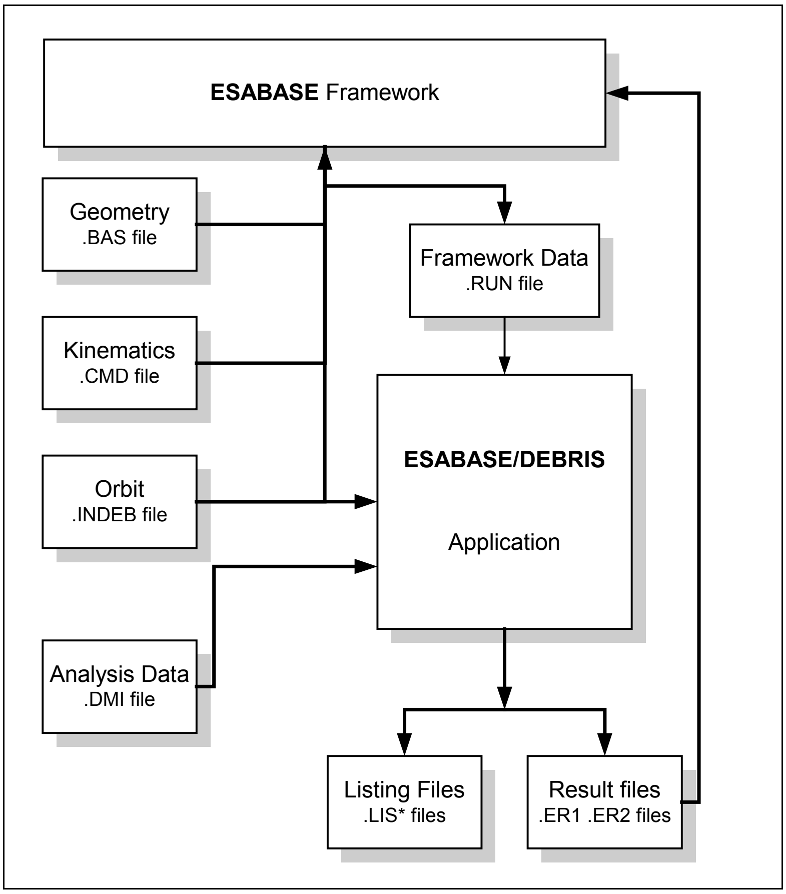


Figure 1 ESABASE/DEBRIS within the ESABASE tool

4 Implementation of New Flux Models

4.1 Concept

A so called shell concept was applied for the implementation of the new debris and meteoroid models. This concept allows to keep the changes in the code of ESABASE as well as in MASTER Standard as small as possible.

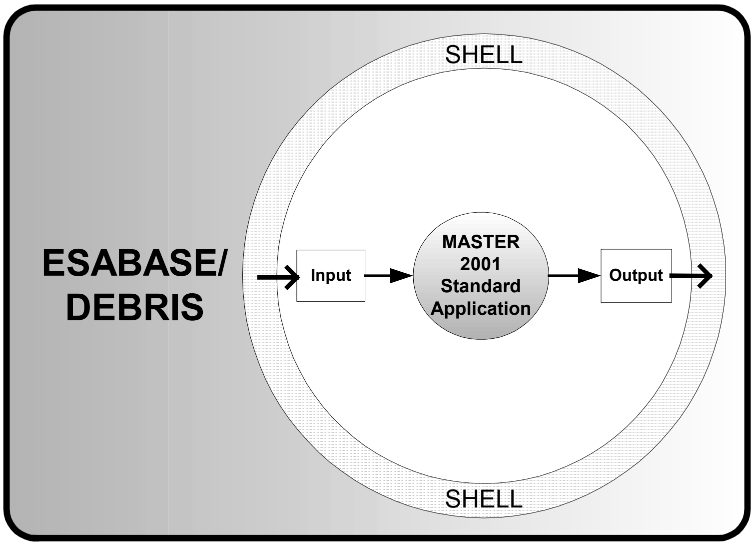


Figure 2 The shell concept of the implementation of the MASTER 2001 Standard application

Figure 2 shows that the "shell", which is some code, provides the interface between ESABASE/DEBRIS and the MASTER 2001 Standard application. The shell initialises and transfers the input data, which is required for a Standard application run. The output of the Standard application is transferred to ESABASE for further processing.

4.1.1 MASTER 2001 Standard Application

4.1.1.1 Overview

The MASTER 2001 Standard application is an upgrade and extension of the MASTER '99 Standard application, which is described in detail in /12/ and /13/. The approach is based on the mathematical theory used by N. Divine /8/ to calculate meteoroid fluxes to detectors onboard probes in interplanetary space. To account for the space debris characteristics, the theory applied by N. Divine was adapted to spacecraft in Earth orbit. Population data describing the Earth's debris environment required by the Divine approach are derived from the MASTER reference population. A sophisticated tool named PCube has been developed by eta_max to process the MASTER population data into the format required by the Divine approach. The basics of the MASTER Standard application, and its implementation in ESABASE can be found in /5/ and /6/.

4.1.1.2 Relevant Features

The MASTER 2001 release of the Standard application offers the following features /15/:

- Reference debris populations are provided for historic and future epochs, where different scenarios for the future evolution of the debris environment are available. Details are given in section 4.1.1.3.
- The MASTER 2001 Standard application is able to process the Divine-Staubach meteoroid populations, and thus one coherent approach, and one tool for both space debris and meteoroids is available in the upgraded ESABASE/DEBRIS software.
- The new Standard application contains an improved population processing philosophy. Two major upgrades were introduced:
  - The automated processing of the MASTER reference population ensures an optimal definition of the required distributions of the orbital elements, considering their various dependencies.
  - Although the underlying theory is based on the assumption of equally distributed nodal lines and perigee positions of the debris particle orbits (resulting in a symmetric population), a way has been found to consider asymmetric population parts /15/.
- The MASTER upgrade provided a callable subroutine version of the Standard application, which was best suitable for an implementation in the ESABASE/DEBRIS tool.

For details of the architectural and detailed design of the implementation of the MASTER 2001 Standard application including the Divine-Staubach model into the ESABASE/DEBRIS tool please refer to the Software Specification Document /3/.

4.1.1.3 Debris Population

One of the most powerful new features of the MASTER 2001 model is the provision of reference populations both for the past, i.e. since the beginning of space flight, and the future. In case of the future analysis, the implementation of the MASTER Standard application in ESABASE is restricted to the reference future scenario ('business as usual'). Due to the restricted hard disc storage targeted for the ESABASE installation package, only this MASTER 2001 default future scenario can be provided for ESABASE.

The MASTER 2001 reference population also used by the Standard application consists of seven sub-populations for all epochs until the reference epoch (May 1st, 2001). Table 1 gives a brief overview of the population characteristics.

Name	origin	particle size range
launch and mission related objects	all trackable objects except those generated by simulated fragmentation events such as explosions or collisions (corresponds to the catalogued objects/TLE background population of MASTER '99), and the Westford needles, which have been released during two American experiments (MIDAS 4 & 6) in the early sixties	10 cm ... 100 m, 0.5 mm ... 4 mm (Westford needles)
fragments	resulting from explosions (low and high in-	0.1 mm ... 100 m

Name	origin	particle size range
	tensity) and collisions	
NaK droplets	coolant droplets released by Russian ROR-SAT's	2 mm ... 4 cm
SRM slag particles	large particles released during the final phase of solid rocket motor firings	0.1 mm ... 3 cm
SRM Al_2O_3 dust	small particles released during solid rocket motor firings	1µm ... 80 µm
paint flakes	resulting from surface degradation	2µm ... 0.2 mm
ejecta	resulting from meteoroid and debris impacts on exposed surfaces	1µm ... 5 mm

Table 1 Sub-populations of the historic MASTER 2001 population snapshots

The future populations are divided into five sub-populations as given in Table 2.

Name	origin	particle size range
Launch and mission related objects	consisting of payloads, upper stages, operational debris	1 mm ... 100 m
Explosion fragments	resulting from satellite or upper-stage explosions	1 mm ... 100 m
Collision fragments	resulting from collisions between large objects	1 mm ... 100 m
NaK droplets	s. Table 1	2 mm ... 4 cm
SRM slag particles	s. Table 1	1 mm ... 3 cm

Table 2 Sub-populations of the future MASTER 2001 population snapshots

Note, that future populations contain all particles larger than 1mm in diameter, while the historic populations contain all particles larger than 1µm in diameter.

4.1.1.4 Flux Analysis Results

In the ESABASE/DEBRIS environment, the results of the flux analysis needs to be provided by means of a limited number of flux spectra for the damage assessment. These spectra are provided for processing within ESABASE/DEBRIS internally, i.e. without writing them to output files. The ray tracing is kept as implemented for the NASA 96 and the MASTER 96 models, where the MASTER 96 model has been replaced by the new MASTER 2001 model.

4.1.2 Divine-Staubach Meteoroid Model

4.1.2.1 Overview

As mentioned above, the Divine-Staubach meteoroid model is based on a mathematical approach, which has been developed by N. Divine /8/. The extensions introduced by P. Staubach comprise the consideration of Earth focussing and shielding effects, as well as the implementation of modified or new sub-populations, respectively /9/.

The meteoroid population used by the Divine-Staubach model is divided into five sub-populations:

- asteroidal population,
- core population,
- A, B, and C population.

For a detailed description of the model theory and characteristics, refer to /8/ and /9/.

4.1.2.2 Implementation

The task to implement the Divine-Staubach meteoroid model into ESABASE was facilitated by the fact that this meteoroid model became an integral part of the MASTER 2001 Standard Application. As mentioned above, the Standard application originally has been designed for debris flux calculation. For this purpose, the population as well as the target orbit is described in an geo-centric equatorial co-ordinate system. However, the meteoroid population is given in the helio-centric elliptical co-ordinate system. Thus, the transformation of the target state vector from the geo-centric to the helio-centric system has been implemented for the evaluation of meteoroid flux.

Due to the fact, that the results of the Divine-Staubach meteoroid analysis have the same format and qualitative content as the MASTER 2001 debris analysis results, it became necessary to process these meteoroid model results within the debris loop of ESABASE/DEBRIS. Some adaptations in the program logic had to be introduced to ensure a correct processing of all combinations of debris and meteoroid flux model combinations.

5 Other Enhancements

In response to the User Requirements a couple of further enhancements mainly addressing the user interface of ESABASE/DEBRIS and some other features were implemented. The following enhancements were performed:

- DMI file

  As mentioned before, the DMI (debris and meteoroid input) file is one of the central input files of the ESABASE/DEBRIS application. Though the application can be operated via the menu, advanced users of ESABASE/DEBRIS often edit the DMI file manually instead of creating it via menu interaction[1]. Due to this fact, the DMI file is one of the main parts of the ESABASE user interface. It thus requires a clear, concise structure and a comprehensive commenting. During former updates of ESABASE/Debris, the structure and 'philosophy' of the DMI file was changed. (see /7/). The changes performed there, however, did restrict the usability of the file

  - The DMI file written by the post-processor was formatted differently than the 'default' DMI file. The pre-processor corrupted the DMI file. DMI files written by the pre-processor were not readable by the application.
  - Keyword used in the DMI file to access damage equations did not work.

The following changes were made:

  - keywords were erased
  - file structure was enhanced
  - the inline documentation was enhanced
  - the pre-processor does no longer corrupt the DMI file
  - some new features considered (switches)

- Enhanced Ejecta Model

  The ejecta model implemented in ESABASE models the effect of particles generated by impacts of 'primary particles'. Those particles generate a cloud of smaller, 'secondary particles' which still may have considerable mass and velocity and which may cause damage at places far away from the primary impact. The ejecta model implemented in the former version of ESABASE suffered from a limited number of materials that could be considered and from the fact that the applied physics was not able to guarantee energy and momentum consistence. The new ejecta model is now able to guarantee energy and momentum balance and takes into account a new material class, namely solar cells.

- Improved Help Function

  The help function available in the former version of ESABASE was incomplete and suffered from some outdated and even contradictory information. It was one of the tasks of this contract to improve the help function and to remove inconsistencies.

[1] The menu is part of ESABASE pre-processor, which also writes a DMI file after the user input has been collected via the menu dialogues. The information flow thus is the same.

- Improved Spot Check Options

  The Spot Check Option allows the user to have an overview of the complete set of parameters used for the analysis. As the help function, the spot check was partially incomplete and needed some update, which was performed in this study.

- Implementation of a cut off angle for the damage equations

  Experimental results have shown that the damage caused by very shallow impacts is higher than predicted by the available damage equations. To account for this fact, a limiting impact angle has to be introduced, which shall be used for impact angles larger than the cut-off value. The cut off angle was implemented.

6 Validation

The validation of the changes made to the tool has been carried out in accordance to the applicable software engineering standards. A software verification and validation plan (see /4/ addressing all user requirements to be fulfilled has been established. The Verification and Validation Plan details what steps are to be taken to ensure proper Software Quality Assurance, sets goals and structures for the project, and determines testing methods. It provides details on the rational behind the single tests, the use cases selected for the tests, variations and special cases in deviation of the use cases, etc. Finally it provides the criteria to judge whether a test has been successful or not.

The described test cases are subdivided into cases addressing the correct implementation of

- the pre-processor
- MASTER Debris Model (Standard Application)
- MASTER Meteoroid Model (Divine-Staubach Application)
- the Post Processor
- the Other Enhancements
- the new ESABASE User Interface

The SVVP contains a total of 32 test cases.

- 8 unit test cases
- 8 integration test cases
- 16 system test cases
- 8 acceptance test cases

A test case definition form containing

- test name, ID, type
- rational behind the test
- description
- variation
- test criteria to be fulfilled
- test results
- comments

has been established for each test case.

All test cases except one were passed, i.e. they have been successfully performed. The failed test case addresses the ray tracing algorithm. The failure could be traced back to the internals of the ray tracing library (raylib), but has not been fixed in the framework of this contract.

6.1 MASTER 2001 Debris Model

Figure 3 depicts a comparison of results provided for an Earth oriented six-sided cube. The following flux models were applied :

- MASTER 2001
- NASA 90
- NASA 96

In case of the MASTER 2001 model, the Standard Application as implemented in ESABASE is used. For all models, the lower size threshold is 1 µm. The figure shows that flux level differences are quite considerable. On those surfaces where also the NASA90 model predicts flux (leading, +azimuth, -azimuth), this model shows the highest flux levels, being about an order of magnitude higher than for the NASA96 model. On those surfaces, the flux level predicted by the MASTER 2001 model is again one order of magnitude lower than for the NASA96 model. On the trailing surface and the Earth and space facing surfaces, the NASA 90 model predicts no flux due to the assumed circularity of all particle orbits considered. Here, the flux level predicted by the MASTER 2001 and the NASA96 model are comparable.

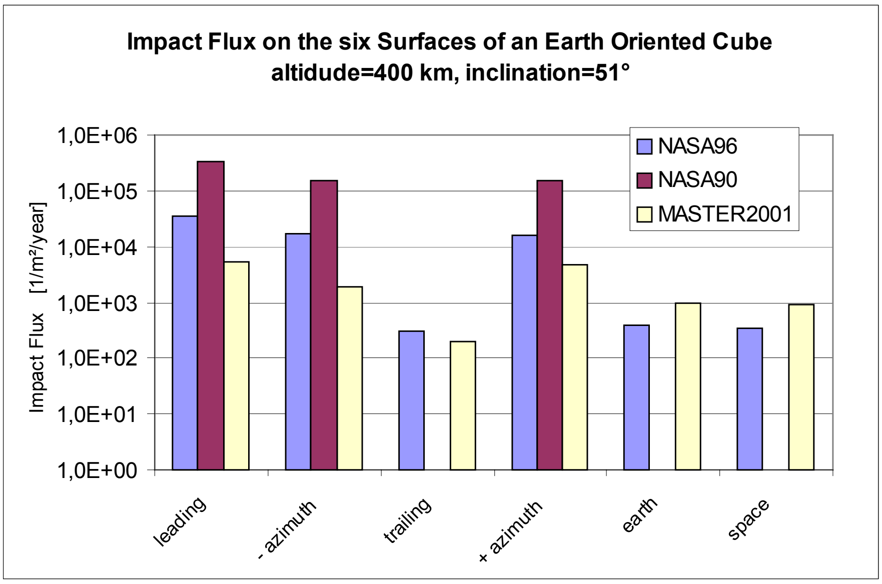


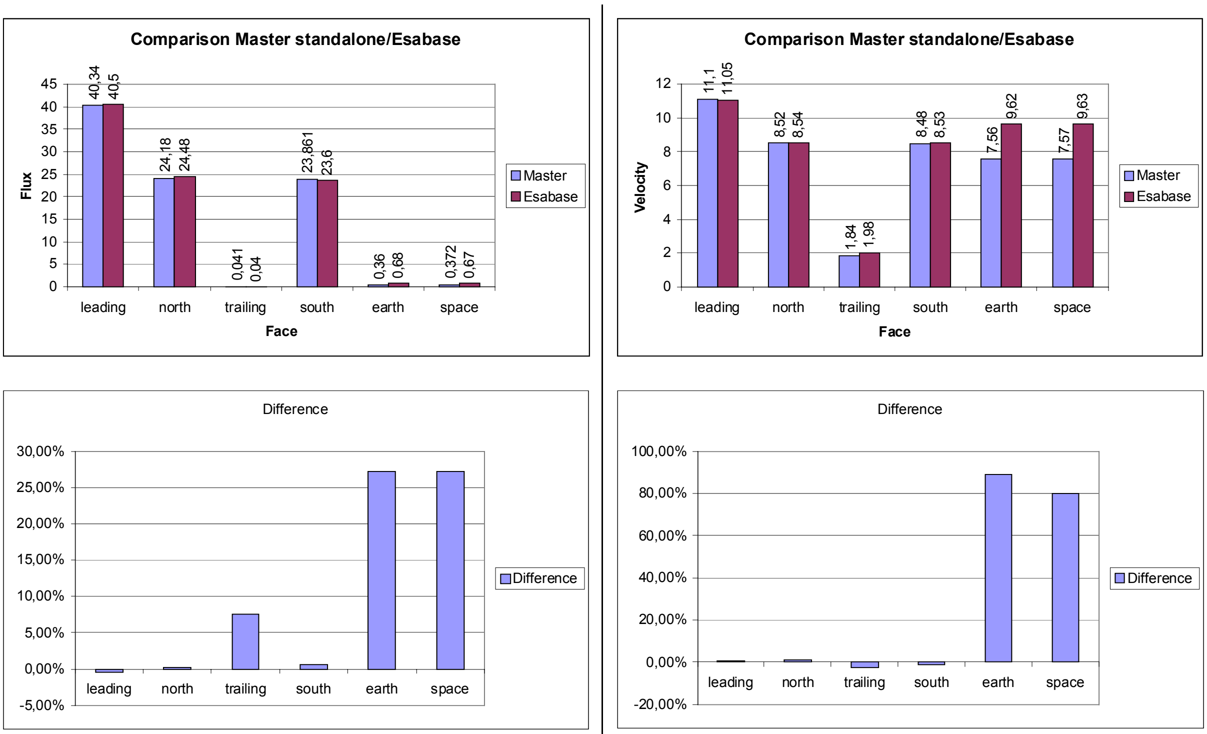
Figure 3 Comparison of Flux level for an Earth oriented 6-sided cube on an ISS-like orbit.

A meaningful test case to ensure the proper working of the newly implemented models in ESABASE is a comparison of results established under usage of

a) the stand-alone tool (e.g. MASTER Standard application) and

b) the same tools integrated in ESABASE.

Such a comparison was subject to the tests applied to ESABASE (a complete survey is given in chapter 6). The results depicted in Figure 4 were established by an application of the MASTER Standard application for particles > 10 micron, the mission duration was from 01.01.2001 to 31.12.2001. All sub-populations were selected, the orbit was an ISS- like orbit with an altitude of 400 km and an inclination of 51.6 degrees. The left part shows the comparison of the overall impact flux level, the right part depicts the comparison of the average impact velocity determined for the single cube sides. All figures include a bar for the MASTER standalone and the integrated version for each side of the cube.



Flux level

Average Velocity

Figure 4 Comparison of Flux level and average impact velocity for an Earth oriented 6-sided cube on an ISS like orbit.

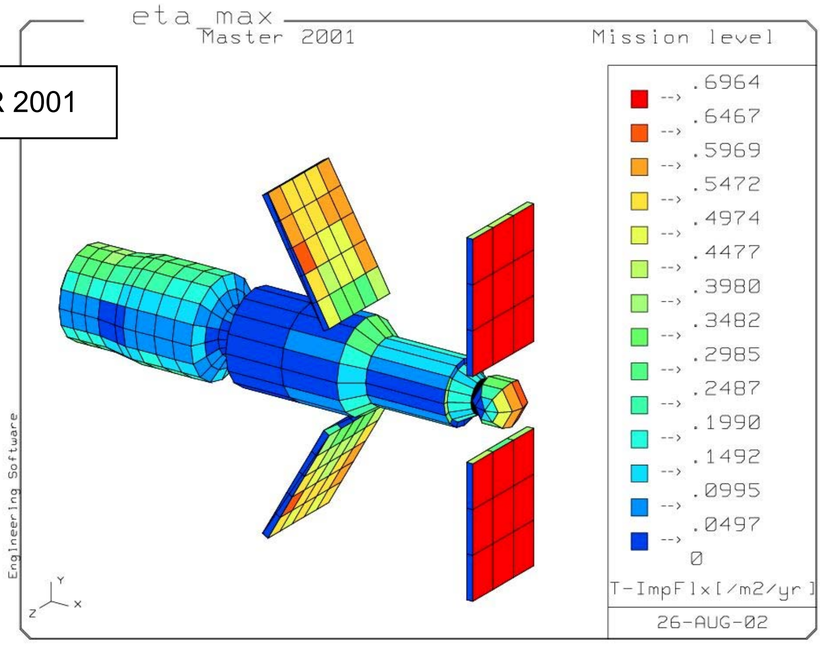
The comparison shows a very good agreement of the impact flux characteristics. As expected, the leading side shows the highest flux, followed by the north and south sides, which show a fairly equal flux level. Small fluxes are observed on the Earth and space side. The trailing edge of the cube shows only very small fluxes. For all sides having a significant flux level, the relative difference between the results obtained from the MASTER stand-alone tool and the integrated tool are very similar. For the Earth and space side the relative difference is larger than 25%, these sides, however are not representative due to their small flux levels.

The comparison of the average impact velocity also shows a good agreement. Only in case of the non-representative Earth and space pointing sides the differences are considerable. A complete set of the comparison results can be found in /4/.

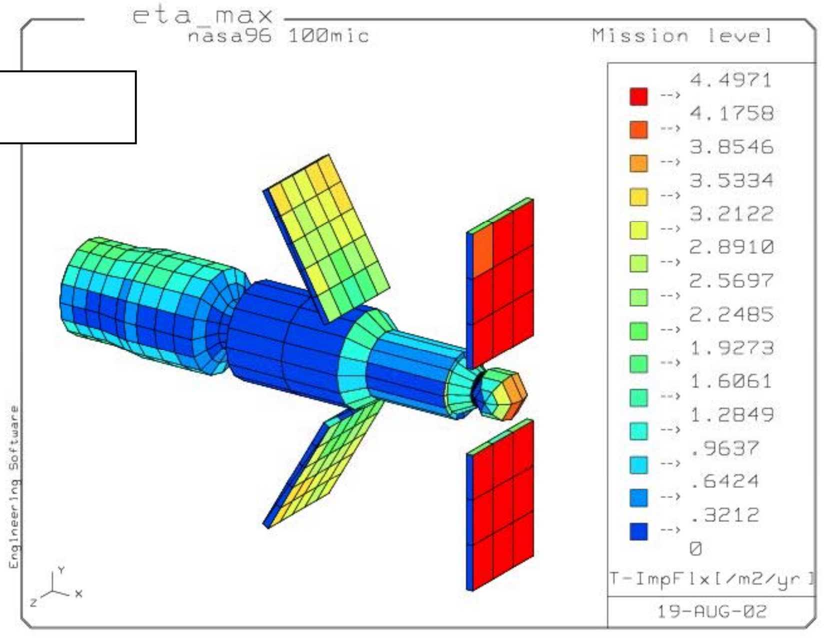
The flux and velocity differences for those sides of the cube which are receiving very low flux contributions can be traced back to the poor Monte-Carlo sampling during the ray-tracing process.

Figure 5 depicts the results of an impact flux analysis to the ATV spacecraft under application of the already mentioned three debris models. The lower particle size level is 0.1 mm (100 microns).

MASTER 2001



NASA 96



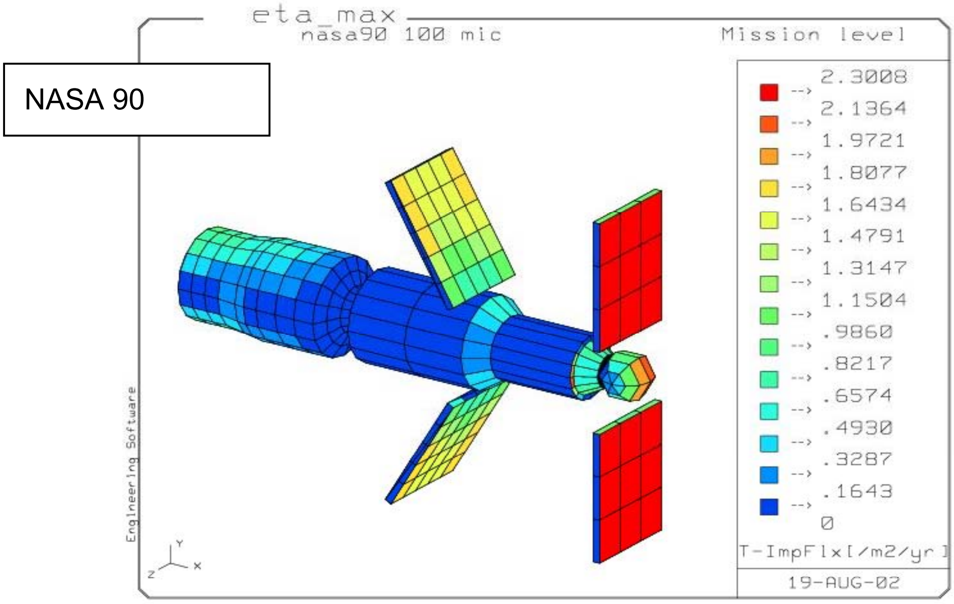


Figure 5 Application of ESABASE/DEBRIS to ATV, Impact Flux

The overall signature of the impact flux distribution over the spacecraft geometry is quite symmetric with respect to the x-z-plane. All three models indicate that the highest flux levels have to be expected on the augmentation wings while the main spacecraft body shows fairly low flux levels. Due to higher azimuth angles, the MASTER 2001 model predicts comparatively high flux levels also at aft augmentation wings and the rear part of the spacecraft body. The mean flux level predicted by MASTER 2001 is about one order of magnitude lower than the level predicted by the NASA96 model. It should, however, be noted that this difference depends on the considered size threshold.

6.2 Divine-Staubach Meteoroid Model

Figure 6 depicts a comparison of results gained from the application of the Grün and the Divine-Staubach meteoroid model to the ATV spacecraft.

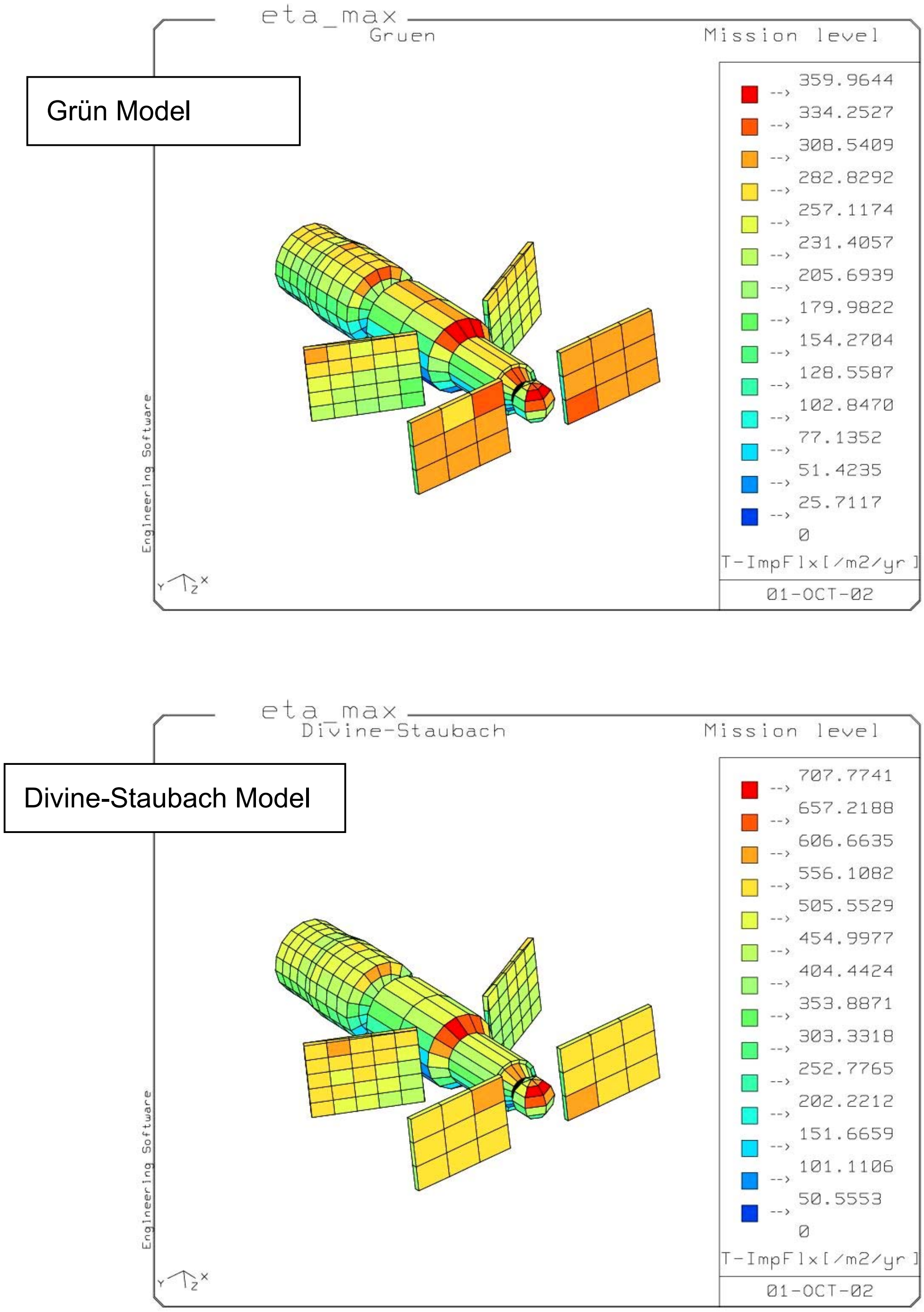


Figure 6 Application of Meteoroid Models implemented in ESABASE/DEBRIS to ATV, Impact Flux from particles larger than 10 µm

In contrast to the debris models presented before, the flux characteristics now is more omni-directional, resulting from the highly eccentric and highly inclined non-Earth orbits of the meteoroids. The overall impact flux characteristics are in a good agreement.

6.3 Enhanced Ejecta Model

The proper function of the ejecta model has been tested by means of different test cases. In addition to the calculation and comparison of the total momentum and the total energy of the ejected particles with the values of the impacting particle, the results of the ejecta model are demonstrated by means of an open cube structure as given in Figure 7 and Figure 8. A single particle impact on the center element of the y-z-plane has been simulated. The target material has been specified as "ductile", 500 secondary rays have been considered.

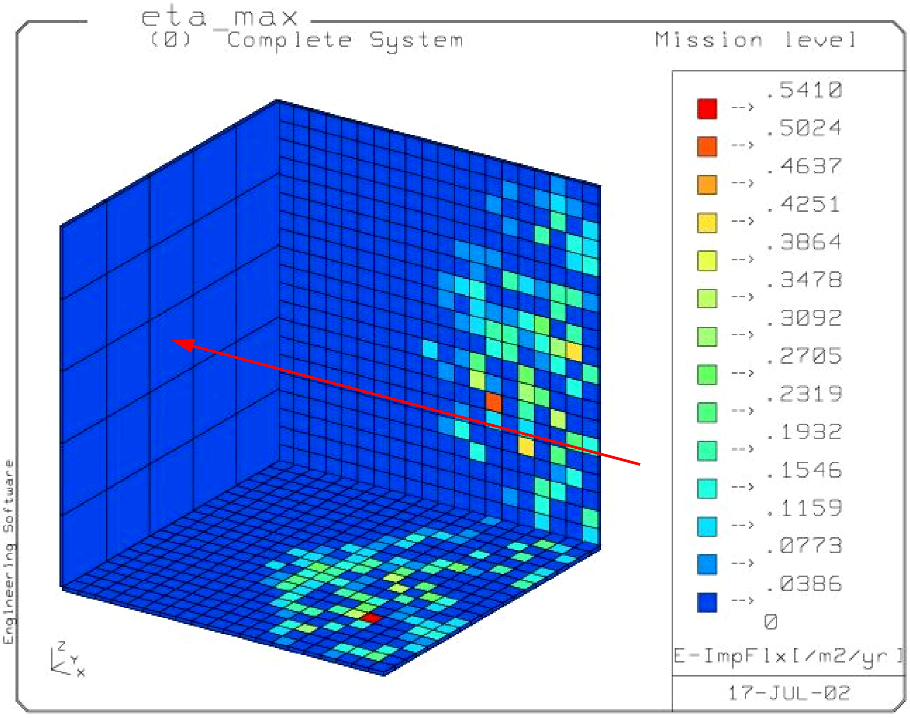


Figure 7 Secondary ejecta flux; impact angle 0°

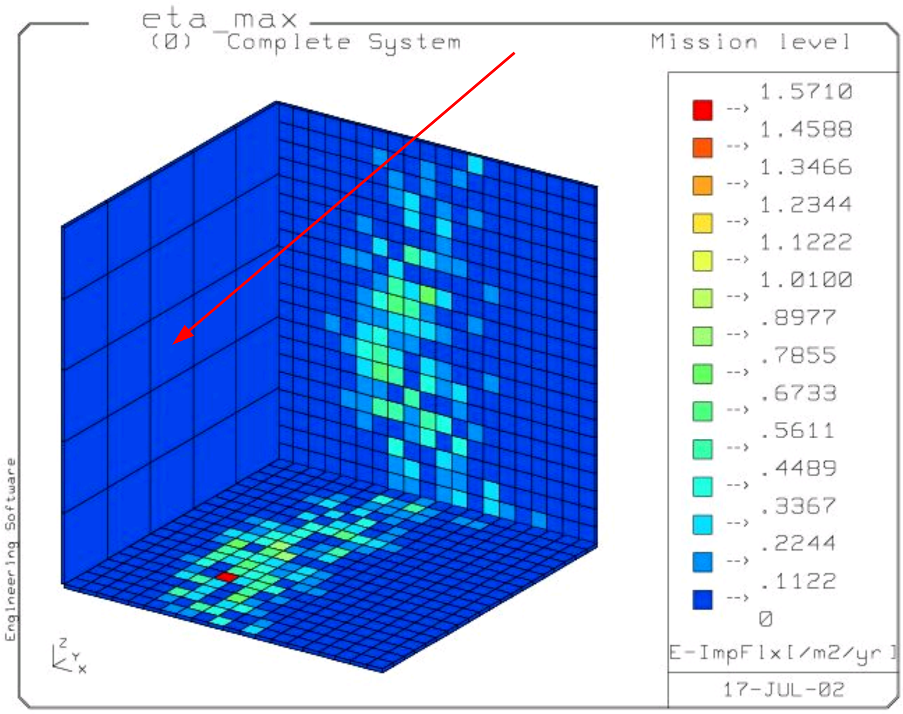


Figure 8 Secondary ejecta flux; impact angle 45°

Figure 4 shows the results for an impact angle of 0 degrees, i.e. the primary impact occurs normal to the y-z-plane. The secondary flux patterns on the x-y-plane and the x-z-plane are very similar as expected. If the impact angle is set to 45 degrees by rotating the primary impact velocity vector towards the z-axis (Figure 5), the main secondary flux appears on the x-y-plane. It can be seen that the ejection angles in flight direction of the primary particle (x-y-pane) are somewhat smaller than those perpendicular to the flight direction (x-z-plane).

The example test case explained above yielded the expected results, and was classified as ‘passed’. A comprehensive collection of all test cases performed for ESABASE is given in /4/.

7 Summary and Conclusions

The following conclusions addressing the here performed upgrade of the ESABASE/DEBRIS tool can be made:

- **state-of-the-art debris and meteoroid flux models have been successfully implemented**

  The ESA MASTER 2001 space debris model and the Divine-Staubach meteoroid model are now part of the ESABASE package. Both models can be applied together with all other features of ESABASE and represent a significant step forward in the applicability and actuality of the flux models implemented in ESABASE.

- **A significant extension of the ESABASE/DEBRIS analysis capabilities was performed**

  The analysis capabilities of the flux models available in ESABASE could be significantly enhanced. Due to the capabilities of the MASTER Standard application it is now possible to analyse also GEO orbits or highly eccentric GTO orbits. Furthermore, the application is now able to consider realistic population snapshots between 1980 to 2020, if the MASTER Standard application is used for the flux analysis.

- **An extensive test program was performed.**

  A total of 32 test cases were defined and performed in order to ensure the proper implementation for all new features.