CNES tools and methods for de-orbit and re-entry trajectories evaluation

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Abstract

In the frame of the FSOA and as responsible of its own satellites operations, CNES needs efficient tools for evaluating de-orbit strategies and risks related to space operations. The first set of tools is used to foresee re-entering orbit evolutions. PSIMU perimeter is for short durations (typically some days) as OPERA is used for some month's propagations and STELA for long-term propagations. The second set is devoted to de-orbit maneuvers: DOORS deals with "classical" de-orbit strategies as SIRENA is in charge of "Assisted Natural Reentries" ones. At last, DEBRISK (for aerothermal models) and ELECTRA (Monte Carlo simulations) evaluate the ground population risk.

1. Introduction

1.1 Context

CNES needed to develop and use Flight Dynamics software both for studies and analysis but also for operational applications. Naturally, the need to build these tools on a common reliable basis appeared as necessary since the very beginning. Thus, in the 70's and the 80's, first basic libraries as the famous MSLIB appeared. The common used language was of course FORTRAN (FORmula TRANslator) which was actually a good choice at that time. Then, based on these basic libraries, many tools were developed as PSIMU as early as 1991!

Then, in 2010, after some trade-off, CNES decided to use the Java™ language to upgrade its old generation software suit (see Figure 1) in parallel to other Scilab™ language developments. Indeed, Java™ language appeared as the « favorite » one for several reasons as the development environment, the user community or its portability. Other advantages "appeared" later as the potential of evolutivity thanks to heritage and interface mechanisms. Of course, "favorite" did not mean the best for each criterion but considering a global perimeter.
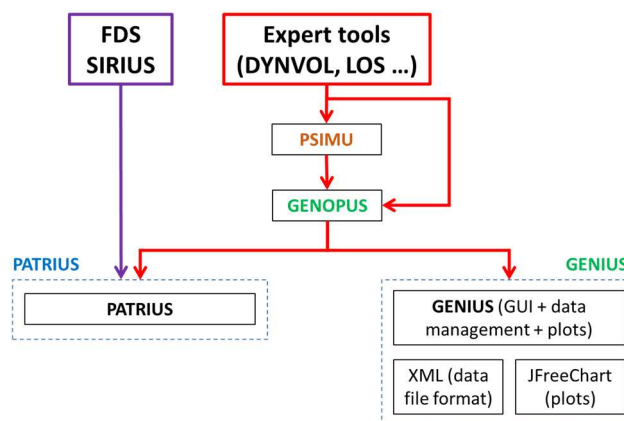

Figure 1: CNES Java S/W suit

Part of this package, this paper will focus on expert tools dedicated to the determination of de-orbit and re-entry strategies to be used in the frame of the French Space Operations Act (FSOA) but also for its operational activities.

1.2 Re-entry expert tools

The first set of tools corresponds to the ones used to foresee short, medium or long-term orbit evolutions that could lead to re-entry on the Earth. Depending of this time horizon and of the available inputs, three different software are available. The first one is PSIMU for numerical propagations, so mainly used for short ones (typically some days). It can model many orbital perturbations as well as maneuvers or attitude motion, and thus get a relatively precise prediction of the trajectory. The second one, OPERA, is used for propagations over some months with some filtering on a set of initial TLE (Two Line Elements). This tool is currently used in CNES operational procedures to predict potentially risky future re-entries. At last, STELA is the CNES reference tool for long-term semi analytical propagations. It allows determining if a mission is compatible with a 25 years duration for LEO orbits or 100 years for geostationary graveyard orbits. Note that these three tools are freely available for download via a dedicated CNES website (https://www.connectbycnes.fr/en/cnes-software).

The second set of tools is devoted to computation of de-orbit sequences of maneuvers. The oldest one, DOORS, deals with "classical" de-orbit strategies leading to an atmospheric re-entry and impacts on a safe zone as the SPOUA (South Pacific Ocean Uninhabited Area). We will see an overview of the current functionalities of this tool which will be used for the next SWOT mission but was previously used during the five ATV missions and for other de-orbit strategies as for the ASTRA-1K de-orbit 20 years ago! A more recent tool, SIRENA, is in charge of strategies that are more complex applied to "Assisted Natural Reentries". These strategies consist in executing maneuvers during several weeks or months to target specific reentry ground tracks to minimize the risk for ground populations. It has been recently deployed in an operational context during an end-of-life experiment. Unfortunately, due to their criticality, these tools are not available outside CNES.

At last, DEBRISK and ELECTRA are both tools to evaluate more precisely the ground population risk. The new DEBRISK methodology associated to dynamics and aerothermal equations considering ablation will allow determining how many debris will survive and what their characteristics will be when they reach the ground. Then, ELECTRA will take in consideration this list of debris as well as many other dispersed parameters to compute, via Monte Carlo simulations, numerous trajectories. It will evaluate a final risk considering failures during the last re-entry manoeuver but also risk in case of natural re-entry if a failure occurs before the last-burn (during the mission or during the first re-entry manoeuver), all of them being weighted by their probability of occurrence. Note that ELECTRA is also operationally used for computation of the risk in case of a failure during each launch from the Kourou launch site (CSG). Both tools are available for CNES external users but are submitted to a specific request to verify that they will only be used in the frame of the FSOA.

2. Re-entry duration estimation

2.1 PSIMU

Originally, PSIMU in the old Fortran suit was very useful as there were no sufficiently high level layers to propose something to propagate trajectories. Only very basic functions as frames or parameters conversions, numerical integrators or forces computation were available. So, PSIMU was there to deal with a lack of such level. PATRIUS library replaces this need by the very powerful capacity of its NumericalPropagator class.

Nevertheless, another need was to propose to users not only a powerful solution for coding but also a "on the shelf" tool with its own Graphical User Interface (GUI): it is not the problem to code in Fortran, Java^{TM} or Scilab if you just want to propagate an orbit. So, it has been decided to build a PSIMU Java^{TM} version, at least with its GUI and batch version. However, thanks to Java^{TM}, it is very easy to access to the PSIMU main class and therefore use the core of PSIMU internally in other expert tools.

Therefore, this Java^{TM} version of PSIMU is a tool allowing propagating trajectories around the Earth. These trajectories may be elliptical ones (all kind of orbits, from LEO to GEO passing through MEO or HEO), hyperbolic ones … and of course atmospheric ones!

PSIMU is usable via three modes:

- ➢ *GUI*: its utilization is made user-friendly thanks to a graphical user facilitating context elaboration and results exploitation,
- ➢ *Batch* using a context file (in *XML* format),
- ➢ *Library* via its *Java* interface. This mode allows using PSIMU inside higher-level tools (orbit restitution, maneuvers computation …).

PSIMU initialization is made by:

- ➢ The initial orbital parameters definition (epoch, frame, coordinates) with a great number of available options.
- ➢ The vehicle modelling:
    - o Different vehicle shapes (sphere, cylinder and parallelepiped) with or without solar panels,
    - o Dimensions or surfaces,
    - o Aerodynamic characteristics and/or radiative pressure ones,
    - o Propulsive characteristics (engines, tanks).
- ➢ A maneuver sequence (optional) including impulsive maneuvers and/or continuous ones
- ➢ A sequence of attitude laws (optional) ; indeed, if **PSIMU** does not manage 6 Degrees Of Freedom (DOF) motion, it owns as input data, attitude laws depending on orbital events, allowing to know at every moment the vehicle attitude and thus, to deduce from it the forces applied to the vehicle.
- ➢ Numerical integrator parametrization (*Runge Kutta* or *Dormand Price*) with, for usual applications, default settings.
- ➢ Choice of force models within:
    - o Potential with several available models and the possibility to manage degree and order of zonal and tesseral terms.
    - o Other bodies attraction as Moon or Sun via analytical or numerical ephemeris.
    - o Atmospheric forces using different atmospheric models and their associated settings.
    - o Solar radiative pressure (direct or rediffused one).
    - o Oceanic and terrestrial tides.

PSIMU also allows setting its output data within several tens of variables, the output frame and, of course, the output step. A graphical interface for plots is also integrated.
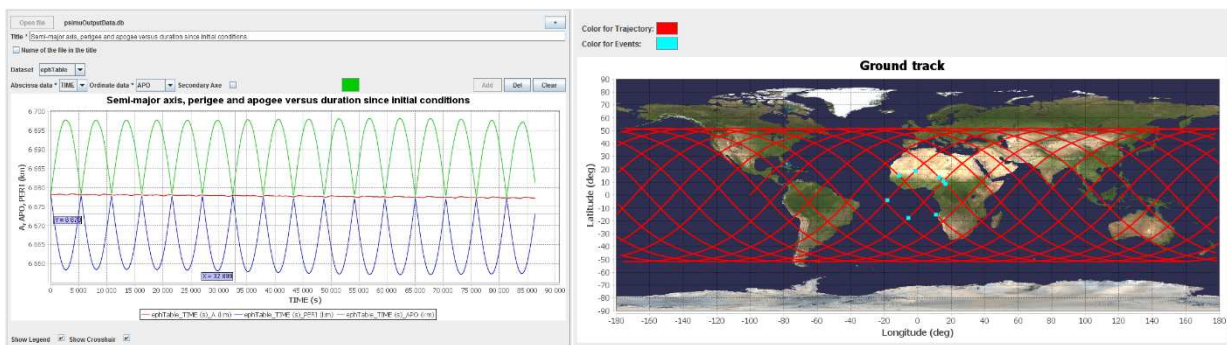

Figure 2: PSIMU plots

Application to re-entry trajectories is available as most of its atmospheric models goes up to an altitude of zero km. Moreover, the definition of aerodynamic characteristics includes drag or lift coefficient constant or depending of altitude, Mach number or AoA (Angle of Attack). Attitude laws may also be defined using AoA, bank and sideslip angles. Therefore, it allows predicting impact points as for the Tiangong re-entry …
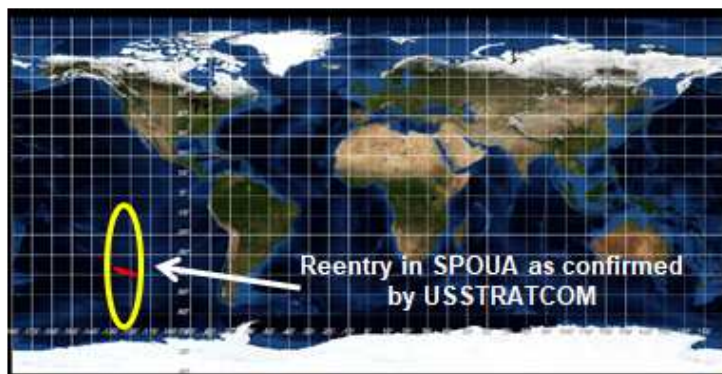

Figure 3: Tiangong final impact locations prevision (2nd April 2018 00)

Since several years, PSIMU is freely available, now via this http://www.connectbycnes.fr/en/psimu new address and a dedicated Wiki may give a lot of information on this tool (http://psimu.cnes.fr).

2.2 OPERA

OPERA is a tool allowing to estimate long and middle term Earth reentry dates (some months to one week in advance) thanks to Two Lines Elements (TLE). It also allows computing the information on other parameters as surface on mass ration (S/M) or maneuvers which have previously occurred. At last, OPERA is able to generate automatic PDF reports with a synthesis of maneuver activity of a given object.

As PSIMU, OPERA is usable via three modes: GUI, batch and Java^{TM} API.

Its initialization is made by:

- A list of initial orbital parameters thanks to TLE,
- Solar activity files,
- Several other specific parameters such as the reentry altitude or how to filter TLE inputs.

For flight dynamics aspects, OPERA is fully based on the PATRIUS library, especially regarding orbit extrapolation. The propagation is done thanks to the STELA propagator (cf. paragraph 2.3) that allows getting reduced CPU time compared to a full numerical propagator while keeping sufficient precision with respect to the reentry date.

OPERA computation performs several steps:

1. Filtering of outlier data among the input TLE datasets. Hence, it is of key importance to detect and filter any TLE outlier that may disturb the correct convergence of the estimation filter.

2. Detection of maneuvering objects (for which the prediction is not performed). Both in-plane and out-of-plane maneuvers are detected.

3. Preliminary estimation of objects area-to-mass ratio, for drag and solar radiation pressure (to be a-priori values for successive final estimation process), based on an innovative method which uses the contribution of conservative and non-conservative forces to the time derivatives of the orbital parameters.

4. Final estimation of the objects' orbit (initial state vector and area-to-mass ratios) based on a weighted least-squares algorithm having the TLE states as input pseudo-observations. This orbit determination is implemented in equinoctial parameters (set used within STELA) to better control the significance given to each parameter (as the argument of latitude for instance) via their a-priori covariance and/or weight matrixes.

5. Prediction of the orbital lifetime for each object by propagation of the estimated orbit up to re-entry (when the object reaches a user-defined re-entry altitude).

Results are synthetized on the console of the GUI but also in dedicated Excel files as also via different kind of plots.

|	Norad Id	Name	Country	Perigee altitude km	Apogee altitude km	Inclination deg	Computation date	Shortest reentry date	Reentry date	Longest reentry date	Reentry date error (days)	SmDragApriori (m2/kg)	SmDragRefined (m2/kg)	Sm
2	10479	DELTA 1 DEB	US	234,020191	261,370299	29,0708	2011-11-24T00:00:00.000	2011-11-20T01:12:55	2011-11-30T15:36:55	2011-12-11T06:00:55	10,6	0,059161	0,054579	
3	10582	SL-3 R/B	CIS	168,462746	177,482313	81,1592	2011-11-24T00:00:00.000	2011-10-24T17:43:27	2011-11-01T10:31:27	2011-11-09T03:19:27	7,7	0,004989	0,006434	
4	24822	ARIANE 44L DEB (SPELDA)	FR	159,87085	259,709561	6,7829	2011-11-24T00:00:00.000	2011-10-16T03:36:17	2011-10-22T20:24:18	2011-10-29T13:12:18	6,700006	0,033289	0,032106	
5	28131	DELTA 2 R/B(2) (PAM-D)	US	0	0	0	2011-11-24T00:00:00.000				0	0	0	
6	37949	CZ-3A R/B	PRC	0	0	0	2011-11-24T00:00:00.000				0	0	0	
7	21321	DELTA 1 DEB	US	306,869143	344,85534	99,3248	2011-11-24T00:00:00.000	2011-11-17T23:13:57	2011-11-22T01:37:57	2011-11-26T04:01:58	4,100006	0,591236	0,22698	
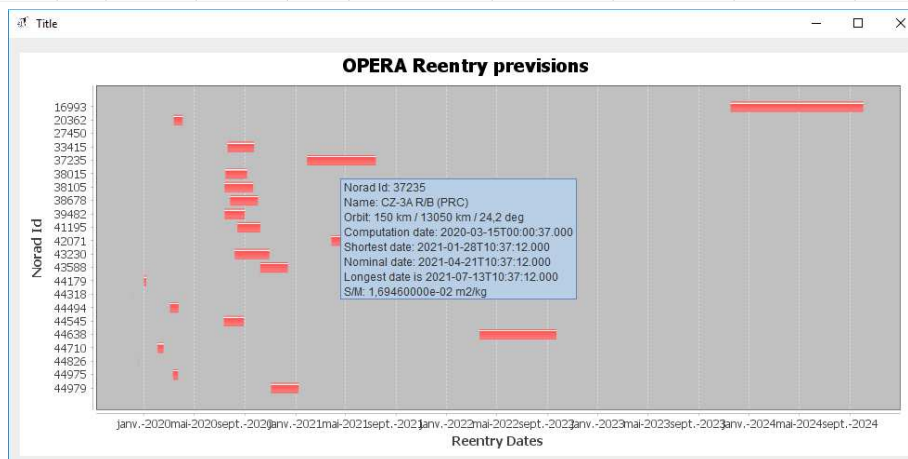
Figure 4: OPERA re-entry previsions

To select the objects to study, OPERA proposes different solutions:

> ➢ To enter directly the Norad Id with the possibility to enter several numbers.
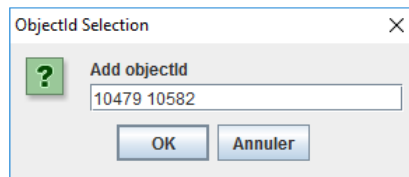
Figure 5: OPERA selecting objects based on Norad Id

> ➢ To filter on some criteriae based on the object characteristics or the orbits to follow
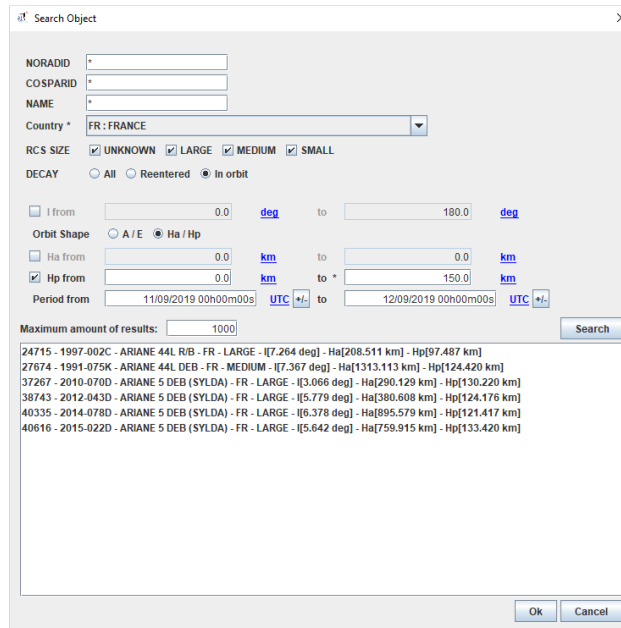
Figure 6: OPERA selecting objects based on characteristics and orbit criteriae

As PSIMU, OPERA is freely available via this http://www.connectbycnes.fr/en/opera new address and a dedicated Wiki may give a lot of information on this tool (http://opera.cnes.fr).

2.3 STELA

The main role of STELA (for Semi-analytic Tool for End of Life Analysis) is to check whether a satellite will comply with the FSOA rules concerning the protection of LEO and GEO regions (lifetime and protected regions crossing of disposal orbits).

Aimed at long-term simulations, STELA software is based on a semi-analytic extrapolator method. The short periods have been removed from the evolution of orbital elements, allowing a large save of computation time without losing precision on long term (several years) mean evolution. The integrator is numerical and based by default on a sixth-order Runge-Kutta method (the classical fourth-order Runge-Kutta method can be chosen instead in the advanced parameters file located in the configuration folder). The combination of those two methods explains why the propagator is said to be "semi-analytic".

Since the first STELA version in 2010, three dynamical models (referred to as LEO, GEO and GTO models) have been developed and tuned for an efficient propagation of LEO, GEO and GTO orbit types. The GTO model is the most generic (because it is able to deal with eccentric orbits), complete and precise one. Since STELA V3 (2015), only the previously so-called "GTO dynamical model" remains in STELA software and is now referred to as "STELA dynamical model". Then, whatever simulation the user chooses (LEO, GEO, GTO), the STELA dynamical model will be used to propagate the orbit. STELA is used with different settings for the dynamics, depending on the orbit type. For example, a 4x4 earth gravity model can be chosen for a GEO propagation, a 7x0 earth gravity model can be chosen for most of the LEO propagations and a 7x7 earth gravity model can be chosen for the GTO propagations (these are the STELA default settings for these orbit types). A complementary acceleration is also considered depending on the choice of the reference frame (can be MOD, ICRF or CIRF, ICRF being the default value since it is inertial).

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The types of perturbations, which can be accounted for in the propagation, are described in the following table:

Perturbation	STELA model
Earth's gravity field	Recurrence formulation for Zonal terms. Generic formulation for Tesseral terms. J_2 included
Solar and Lunar gravity	Yes
Atmospheric drag	Yes (Oblate Earth, Rotating Atmosphere, Simpson Quadrature)
Solar Radiation Pressure (SRP)	Yes (Simpson Quadrature)
Earth's shadow for SRP	Yes (The Earth shadow is a cylinder)
Solid tides	orders 2 and 3 (Sun and Moon contribution)
Numerical integrator	Sixth-order Runge Kutta

Table 1: STELA type of perturbations

Once the initial conditions are set, STELA is able to determine when the object will re-enter inside the Earth atmosphere … and if it respects or not the FSOA rules!
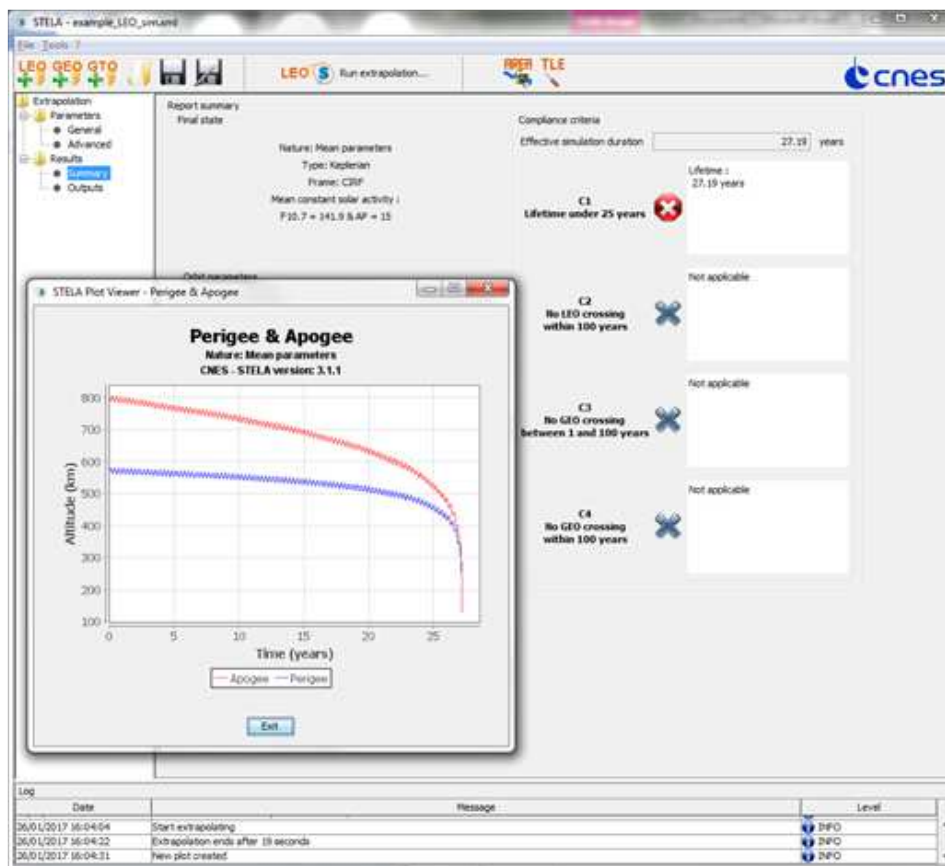
Figure 7: STELA results

If, this time, STELA does not have its own Wiki, it is also available via this http://www.connectbycnes.fr/en/stela new address.

3. Maneuvers

In this chapter, we will describe two different tools in charge of de-orbit maneuvers sequence computation. The first one (DOORS) corresponds to "classical" controlled reentry strategies as the ones used for the ATV missions as the second one (SIRENA) deals with the new concept of natural assisted re-entries. At the present time, none of them is available outside CNES.

3.1 DOORS

DOORS is a tool allowing computing deorbit maneuvers strategies as well as impact areas after atmospheric re-entry. Originally, it was inspired from the operational Russian tool SADIK and was developed (in Fortran90) in 1998 for ATV needs. Then, it was adapted and modified to take into account other needs as, for example, during the ASTRA-1K re-entry where a solar pointed attitude mode had to be implemented during the thrust phase (not needed for ATV missions) or, more recently for the SWOT (Surface Water Ocean Topography) which will execute a controlled re-entry at the end of its mission. Nevertheless, the Java^TM version does not include anymore the dedocking phase.
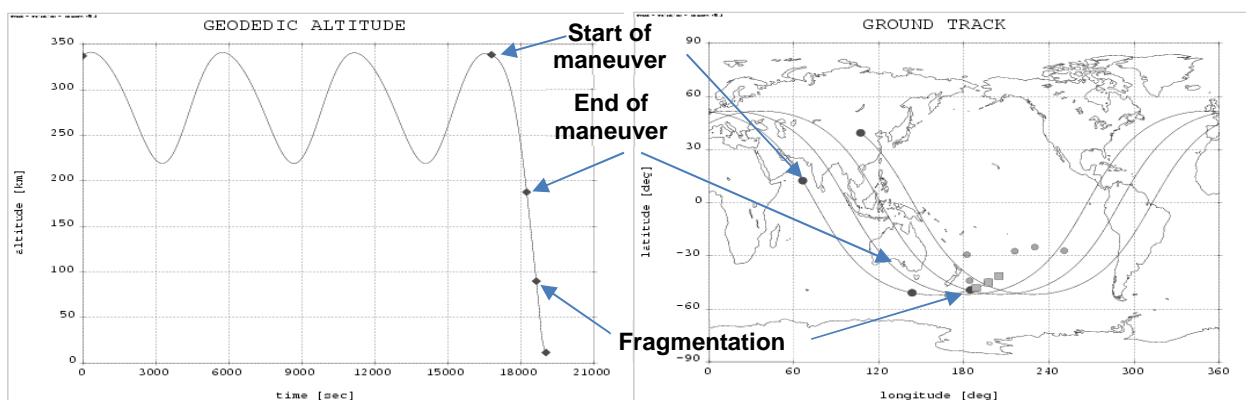
Figure 8: ASTRA-1K re-entry
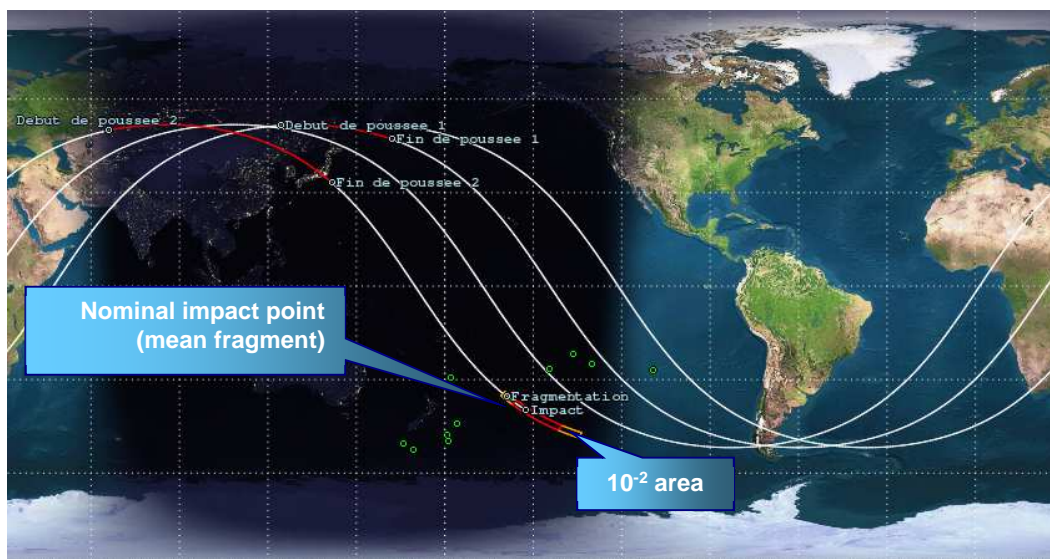
Figure 9: ATV Jules Verne re-entry

DOORS has two different modes:

> ➢ A "manual" mode for which the tool is reduced to a simple simulation function: based on initial orbital parameters, a vehicle description and a maneuver scenario, it simulates an orbital then re-entry trajectory up to the ground.
> ➢ An "automatic" mode in which it is used as a design tool in order to build a deorbit scenario including maneuvers computation and positioning to reach a targeted perigee and/or an aimed nominal impact point.

In each case, impact areas, directly linked to safeguard criteria (10^{-1}, 10^{-2}, 10^{-3}, 10^{-4} and 10^{-5}) may be computed.

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3.1.1 The automatic mode:

In case of time iteration mode (by default), the principle is to search for the maneuver epoch (always the first one) in an iterative way to reach a nominal impact point. This point is specified:

➢ Either in latitude: in such a case, we must give additional information to know if searching will be on an ascending or descending ground track.

➢ Either in longitude.

Eventually a daily orbit number is given (Russian then ATV notion). It is simply an orbit counter that is reset every time the geographical longitude of the ascending node will cross the 20º meridian. Thus, during a sidereal day, there is a given amount of orbits and when aiming a specific daily orbit number, DOORS will compute a re-entry corresponding to a trajectory with roughly the same ground track no matter the epoch required for the reentry.

It is also possible to iterate, not on the maneuver epoch but on the initial orbital conditions. This way of iterating is interesting in case of mission analysis studies in order to define quickly the right orbit just before starting the deorbit scenario (especially in case of initial eccentric orbits). Using this mode, DOORS will iterate on the argument of perigee to reach the right latitude or longitude impact and on the RAAN for the daily orbit number.

User may choose maneuvers definition by duration, ΔV, ergol consumption or for reaching a given perigee altitude. Except for the first one, all maneuvers are centered on an apogee position.

3.1.2 Impact areas:

Three kind of fragments are defined:

➢ The "mean" one that will be used to compute the nominal impact point for the maneuvers computation automatic mode.

➢ The "short" and "long" fragments which will give the furthest impact points (resp. heel and tail points).

On this basis, we have the possibility to add dispersions (Gaussian, symmetrical or asymmetrical uniform):

➢ On the atmospheric density and the initial mass (impact on the deceleration level).

➢ On the maneuver(s) via thrust level and direction as well as the ΔV.

For each of these dispersions, distance heel/tail relative to the nominal point will be computed then a quadratic norm will group all the dispersions.

3.1.3 Propagation:

Trajectory propagations are essentially numerical ones, using all basic PATRIUS models and propagators. An important point is the fact that the maneuvers are always considered with a constant continuous thrust, as impulsive hypothesis is not well adapted to such part of a mission.
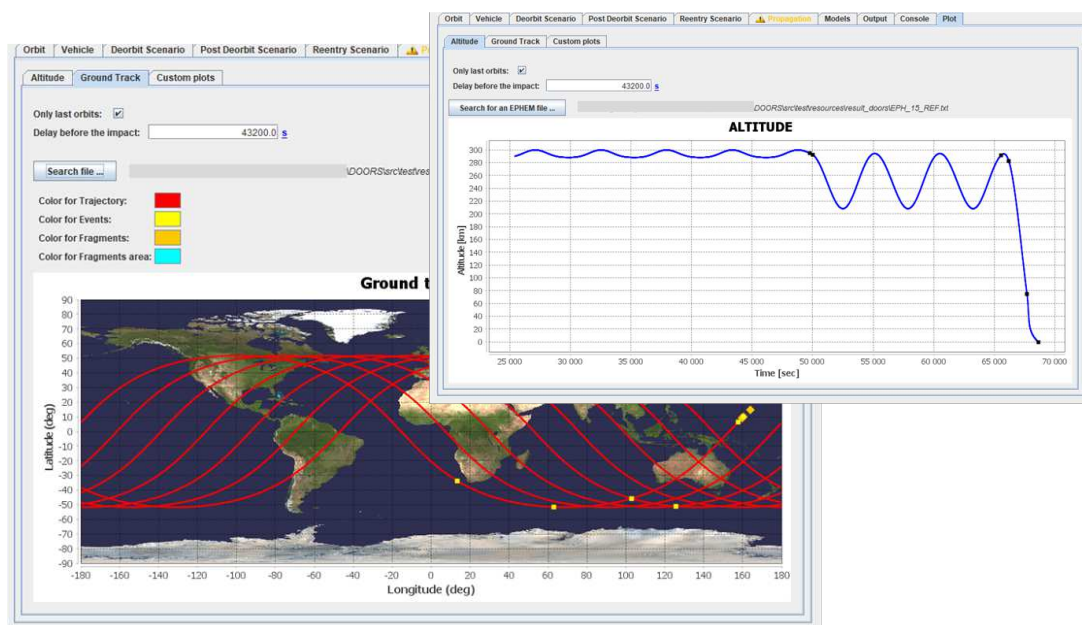

Figure 10: DOORS results

3.2 SIRENA

SIRENA is a CNES tool allowing to propagate natural assisted re-entries, creating the maneuvers strategy and even its control. Indeed, Assisted Natural Re-entry is an attractive alternative to direct re-entry and natural decay. This deorbiting consists in performing multiple manoeuvers to lower the orbital altitudes as much as possible so that the natural re-entry will be very short, allowing to target a limited impact zone on ground and thus limit the human casualty risk. Maneuvers for an assisted natural re-entry can be performed with classical chemical or even low thrust propulsion, contrary to direct re-entry that needs specific propulsion subsystems.

The casualty risk is only reduced if certain specific constraints, like the impact zone length and its relative position to the Earth, are met. To ensure compliance, a precise final re-entry orbit must be reached on a specific date with a good accuracy. Nevertheless, the active deorbiting phase may last several months, implying a not negligible difference between the predicted conditions and the real conditions experienced in orbit. These differences may affect strongly the final orbit, preventing to reach the desired target. Thus, it is necessary to adapt continuously the maneuvers in order to reach the targeted conditions and SIRENA tool meets these requirements.

CNES created the natural assisted re-entry concept in 2015 and started the SIRENA development some years after. By comparison to other tools as DOORS (see paragraph 3.1), it is a relatively recent tool. Anyway, many evolutions occurred since its first version, due to many additional requirements in the different missions studied. Of course, as the other tools, SIRENA uses the Java^{TM} language for its development and all the basic CNES libraries as PATRIUS for the flight dynamics and GENIUS/GENOPUS for the GUI. SIRENA uses also internally PSIMU tool (cf. paragraph 2.1) to perform the propagation.

SIRENA offers two main types of simulation:

- ➢ Computation of the maneuvers strategy given the mission orbit and/or the re-entry orbit.
- ➢ Computation of the control maneuvers strategy needed to follow a nominal previously computed case.

Its initialization mainly needs:

- ➢ The preferences about the simulation:
    - o To compute a reference trajectory or only to control it from an external file
    - o In case of computing this reference trajectory, to use a forward or backward mode. The first one starts from the initial mission orbit to reach a final one as the second one starts from the final target orbit.
    - o The end conditions that may be defined in date, perigee altitude or propellant mass.
- ➢ The target and mission orbital parameters definition (epoch, frame, coordinates) with the possibility to define them in mean or osculating parameters and with a great number of available options.
- ➢ The vehicle modelling with:
    - o Vehicle shapes (sphere, cylinder and parallelepiped) with or without solar panels.
    - o Dimensions or surfaces.
    - o Aerodynamic characteristics and/or radiative pressure ones.
    - o Propulsive characteristics (engines, tanks).
- ➢ Choice of force models within a lot of possibilities (in fact, the same ones as PSIMU):
- ➢ Constraints about the maneuvers strategy as minimum or maximum duration of the maneuvers, eclipse impact on manoeuvres if electrical propulsion … Thanks to its last versions, an important point was to take into account classical operational constraints in order to get a realistic maneuver plan (contingency periods, maneuvers time slots …).

SIRENA produces as an output:

- ➢ Ephemeris including any relevant data (mean orbital elements, dynamic pressure, perigee altitude, etc.).
- ➢ Maneuvers plan.

In complement to the console output, a graphical interface for plots is also integrated (see Figure 12).

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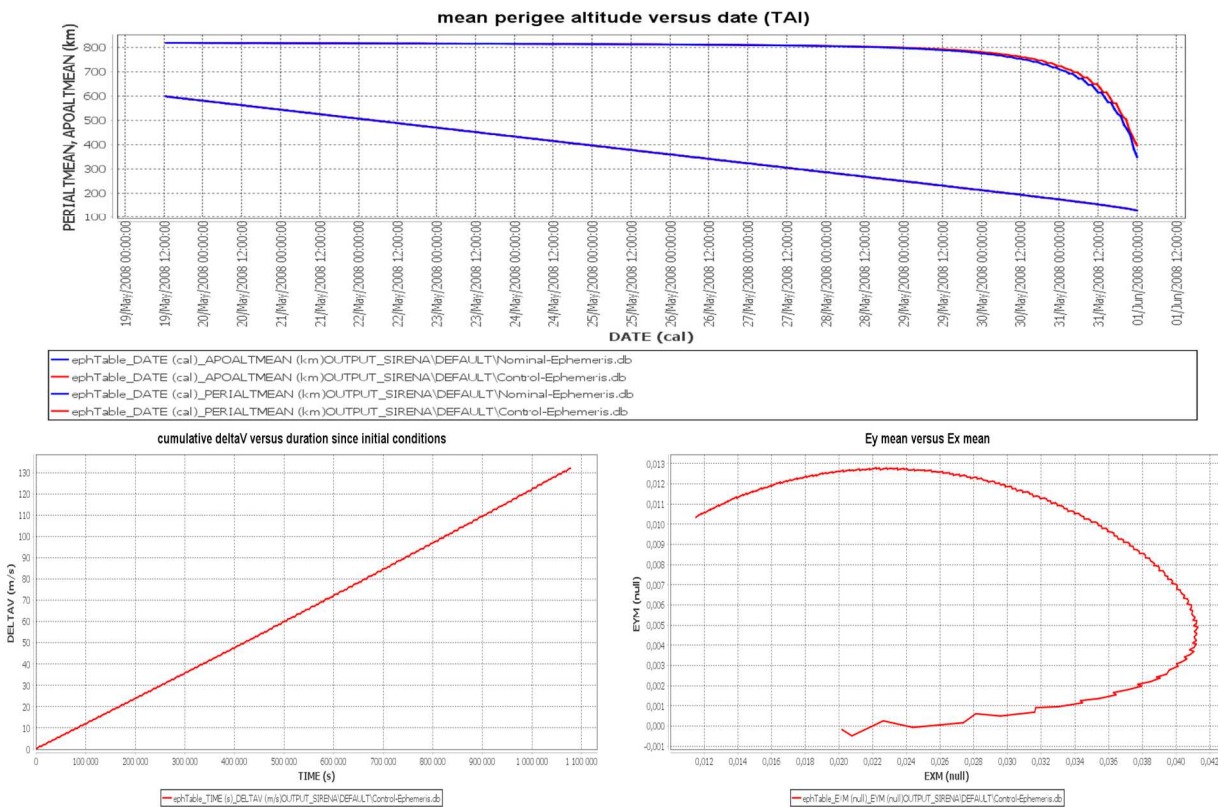*Figure 11: SIRENA reference manevers tuning*

Figure 12: SIRENA plots

4. Risk computation

4.1 DEBRISK

Developed in JAVA[TM] since 2011, DEBRISK evaluates fragments survivability during the re-entry of a satellite in the Earth atmosphere. The DEBRISK approach assumes that the satellite is composed of a collection of independent objects modelled by simple forms (sphere, box, cylinder or plates) or more complex ones (spherical or conical surfaces). The most common satellites materials are available to characterize the fragments but new materials can be added for a better modelling of the ablation.

The trajectories of the satellite and its fragments are computed using PATRIUS CNES flight dynamics library. First, it's a simple integration of the equation of motion from the starting point until the fragmentation altitude chosen by the user (typically around 78 km) or automatically determined. At this altitude, the satellite breaks up and all the fragments are released.

From the fragmentation altitude, the computation is independent for each fragment. The simulation takes into account:

➢ The aerodynamic modelling to determine the drag coefficient used for trajectory computation. We assume that the objects have a tumbling attitude.

➢ The thermal modelling to estimate the heat transfer to the surface of the object and compute the temperature of the fragment. When the melting temperature is reached, ablation of the object begins.

➢ The ablation modelling to estimate the amount of material ablated and compute new mass and dimensions at each time steps.

➢ The propagation of the trajectory taking into account the ablation rate for the surface and mass calculation.

The fragments contained in the satellite can themselves include other "child-fragments". Those child fragments are released when the parent-fragment is completely ablated. The simulation of those objects is then similar to the description given above.

In advanced mode, the heat conduction between object can be activated on condition that conduction coefficients are known. With this option, fragments are warmed by their parent object before their release. Then, those objects are released with a temperature higher than the standard initial temperature of 300K.

For each fragment, Debrisk provide various information on the survivability of the object, among others:

➢ Demise altitude in case of total ablation of the fragment.

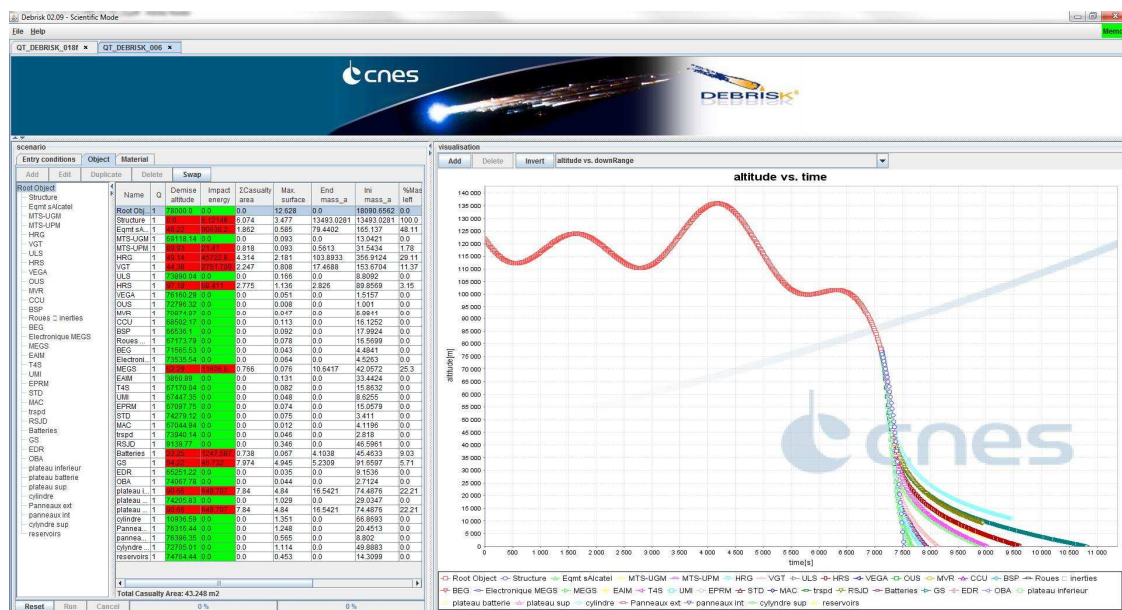➢ Impact energy, remaining mass, casualty area, … for objects which reach the ground.

Figure 13: DEBRISK results

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4.2 ELECTRA

ELECTRA is the more ancient tool developed for FSOA as its development undertook in 2007. The most recent version (V4.4.1) is available since the beginning of 2022. ELECTRA meets the requirement for precise quantification of the risks involved in the launch and the re-entry of a spacecraft. It computes the risk of making a victim due to atmospheric reentries, with or without taking into account protection coefficients. Using a lot of input data as the debris characteristics eventually provided by DEBRISK, ELECTRA can compute the risk of making a victim in several contexts:

➢ RA mode: In this case, the space object (satellite or launcher part) will naturally reenter under atmospheric drag. It is not controlled over a long period and it is impossible to predict the impacts location. The method considers only the latitudes the object flies over, meaning the risk depends on the inclination of the orbit.

➢ RL mode: this context starts from the trajectory of a launching (which is guided by definition) eventually dispersed. The method computes the risk due to failures occurring during this launching phase.

➢ RC mode: this context deals with controlled reentry trajectories following deorbit maneuvers and evaluates the risk associated with maneuver failures.

➢ RF mode: in this case, we consider uncontrolled re-entries but only some days before the final fallout. It is then possible to compute the risk more precisely than in RA mode. This mode is only available since the V4.1 version.

➢ RZ mode: this is the latest mode, implemented since the V4.4 version. It corresponds to the following need: to be able to compute risk for ground populations for a pre-computed dedicated fallout area (that may be more precisely calculated) that may contains specific sensitive zones (as off-shore platforms).

Except for RA and RZ modes, numerical propagations are used. To obtain the impact coordinates (latitude and longitude) and the energy of impact of each fragment, ELECTRA first calculates the trajectory of the intact vehicle from the failure instant until its fragmentation and then the trajectories of each fragment to the ground. This computation is done for each considered propulsion failure

Several sources of dispersion and/or poor knowledge of some parameters can influence directly the impact point of debris:

➢ The initial state vector at the moment of the failure (for Launch and Controlled reentry modes),
➢ The intrinsic characteristics of the vehicle,
➢ The altitude of the feared event (rupture or explosion) leading to the spacecraft fragmentation,
➢ The fragmentation characteristics (including the ejection velocity at the loss of integrity),
➢ The external environment.

Since the effect of these uncertainties on the risk is difficult to predict, the ELECTRA method uses a Monte Carlo process to compute the risk taking into account all these dispersion sources.

The forces taken into account in the computation of the trajectory, both for the spacecraft and fragments are:

➢ The gravitational attraction of the Earth.
➢ The atmospheric forces (drag and lift).
➢ The forces due to solar radiation pressure.
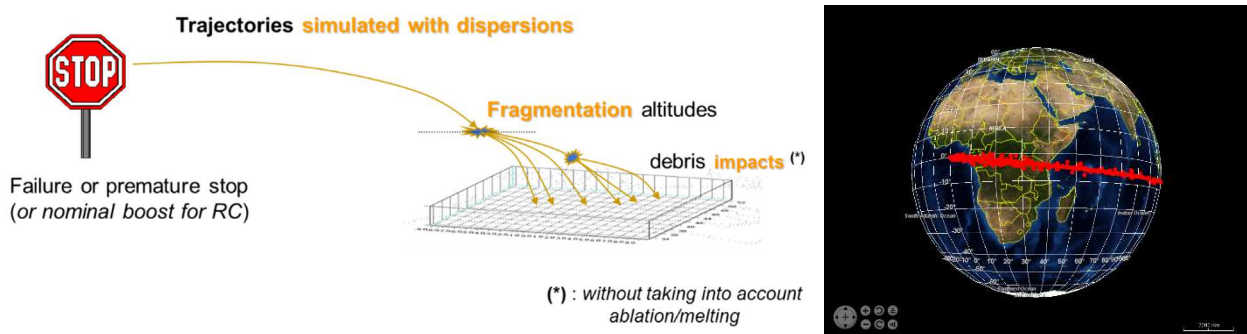➢ The gravitational attraction of the Sun and the Moon.

Figure 14: ELECTRA impact coordinates computation

Moreover, ELECTRA comes with a list of additional tools that the user may execute via its main frame. These tools allow pre or post computations as, for example a fragments editor or an impact location map …
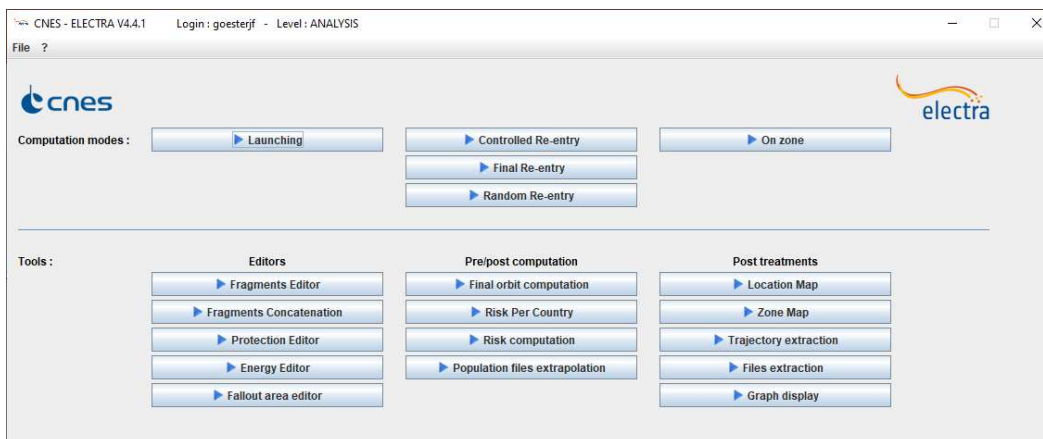

Figure 15: ELECTRA main frame

5. Conclusion

Part of numerous expert tools available at CNES, the ones described in this paper are especially involved in Earth re-entries studies and operations. If most of them exist for many years (more than 30 years for PSIMU!), a great amount of evolutions occurred, reflecting a continuous use of these tools all over these years as well as the emergence of many new situations and needs. By helping to compute smart maneuvers, simulate precise trajectory, fragmentation events, thermal ablation and finally debris impact on Earth together with human casualty, all these tools aim to improve the sustainability of Space activity. Besides all functional improvements, one important but more "software oriented" evolution is the fact that these tools are now written in Java[TM] language allowing to use them more easily on every kind of platforms and then, to be able to distribute them outside CNES for a part of them. Therefore, it is possible to get most of them via the http://www.connectbycnes.fr/ site.
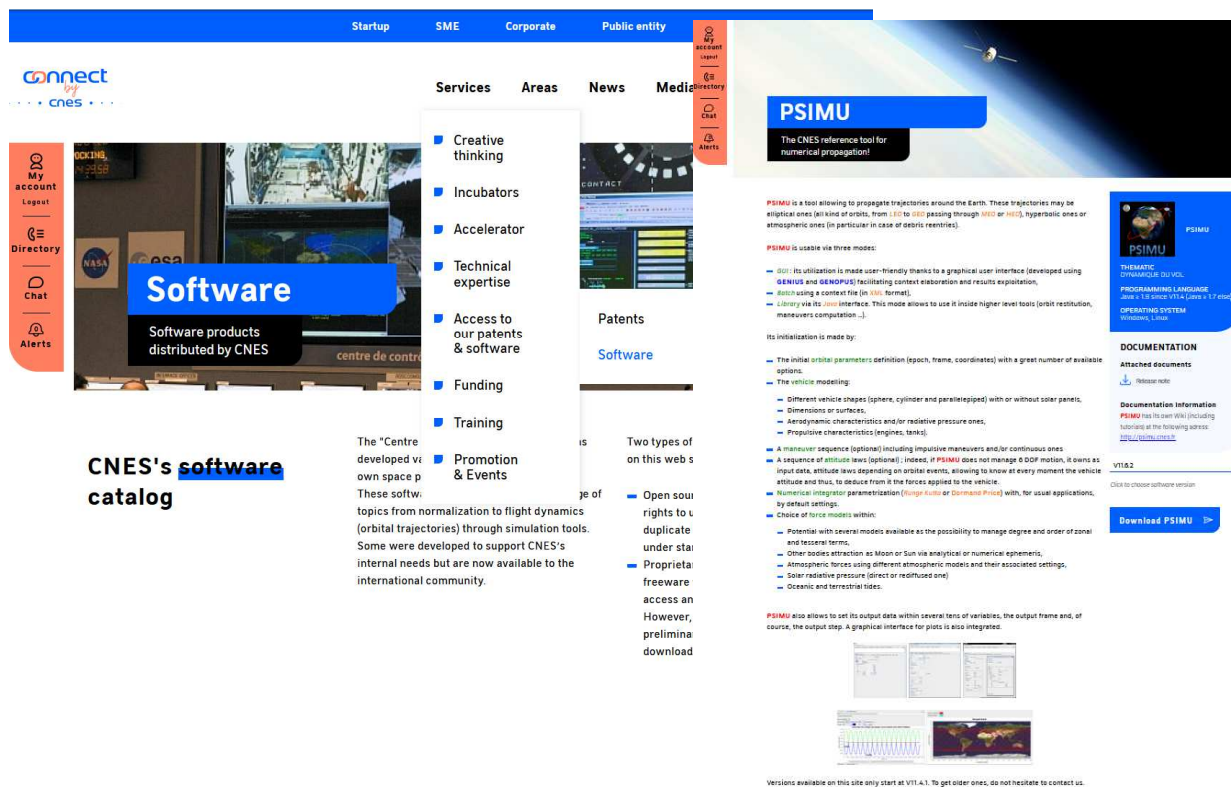

Figure 16: ConnecByCnes website

Thanks to the great amount of uses, these tools are robust and above all well validated mainly because they are all based on the PATRIUS flight dynamics library, which is the core of all CNES tools including the operational SIRIUS Flight Dynamic Subsystem (FDS).

6. References

[1] Goester JF, 2018. Free Java^{TM} CNES Flight Dynamics tools. In 7th International Conference on Astrodynamics Tools and Techniques (ICATT), 6-9 November 2018, DLR Oberpfaffenhofen, Germany.

[2] Juan Carlos Dolado Pérez, Laura Aivar Garcia, Alberto Águeda Maté, Iván Llamas de la Sierra. OPERA: A tool for lifetime prediction based on orbit determination from TLE data. In 24th International Symposium on Space Flight Dynamics (ISSFD), 5 - 9 May, 2014, Laurel, Maryland, USA.

[3] Elisabet Cid Borobia, Claire Frémeaux, Jean-François Goester. Fast re-entry deorbitation with acceptable risk level. In 7th European Conference on Space Debris, 18–21 April 2017, ESA/ESOC, Darmstadt/Germany.

[4] Goester JF, Bellucci A. ELECTRA: new features of the CNES launch and re-entry risk analysis tool. In 2nd International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions Engineering (FAR), 19-23 June 2022, Heilbronn, Germany.

[5] Bellucci A, Goester JF, Omaly P, Christy S, Delmas F. Tiangon 1 Re-entry follow-up by CNES. In 7th International Conference on Astrodynamics Tools and Techniques (ICATT), 6-9 November 2018, DLR Oberpfaffenhofen, Germany.

[6] Omaly P., Annaloro J. DEBRISK V3: CNES tool evolutions for re-entry risk analysis. In 10th International Association for the Advancement of Space Safety (IAASS), 15-17 May 2019, The Aerospace Corporation El Segundo, Los Angeles, California, USA.