Reenpred

REENTRY PREDICTION AND ANALYSIS SOFTWARE

GMV's ***Reenpred*** COTS software is a software designed to perform detailed **analysis of the re-entry process** of objects currently orbiting Earth. This versatile program offers a range of high-level analyses:

- **Orbital Lifetime Estimation**: ***Reenpred*** estimates the approximate re-entry epoch for all objects in the catalogue based on their current orbital information and using semi-analytical propagation techniques.
- **Orbital Re-entry Propagation**: For objects with orbital lifetimes shorter than 60 days, the software propagates the state and its associated uncertainty from the most recent estimate up to the altitude where atmospheric re-entry begins (e.g., 80 km).
- **Atmospheric Re-entry Computation**: ***Reenpred*** evaluates the fragmentation and disintegration process, computing likely trajectories and uncertainties of re-entering objects and their fragments, from the altitude of atmospheric re-entry to Earth's surface impact.
- **On-ground Risk Evaluation**: The software assesses the risk of casualties and fatalities on the ground based on the impact time, location, and corresponding uncertainties.

The **Orbital Lifetime estimation** makes use of the historical orbital information from an object catalogue to **estimate** the **mean elements** of a **semi-analytical propagator** (DSST - Draper Semi-Analytical Satellite Theory). These estimated mean elements are propagated until the object re-enters Earth's atmosphere estimating the re-entry epoch together with its uncertainty through a **Montecarlo** method. The software also allows computing fragmentation as part of the propagation process, computing the re-entry epoch and the associated uncertainty for each one of the simulated fragments.

The **Orbital Re-entry Propagation** consists of **orbital propagation** to compute the time and location of re-entry up to the re-entry altitude, using **different atmospheric density models** for propagation, and computing **visibility events** analysis during orbital re-entry propagation. It is possible to compute the **uncertainty** associated with the re-entry based on a hybrid Kernel Density Estimator + Monte Carlo analysis algorithm.

The **Atmospheric Re-entry Computation** includes the simulation of the **break-up** process with the NASA break-up model at re-entry altitude, simulation of the **disintegration** process (i.e., loss of mass due to burn-up) of the parent object and corresponding fragments, propagation of **trajectory and uncertainty** through Earth's atmosphere of the parent object and fragments, and computation of **visibility events** analysis during the atmospheric re-entry propagation.

The **On-ground Risk Evaluation** covers the computation of **casualty and fatality risk** associated with the re-entry using the GPWv3 Earth population density model, computation of **countries affected** by the re-entry (among a preconfigured list of countries), and computation of the **probability of landfall** and landfall on each country of interest territory.

In terms of run-time performance, ***Reenpred*** can perform an orbital lifetime analysis of 20,000 objects in less than 24 hours running on a single core and can perform a re-entry analysis covering 7 days, assuming a break-up of 50 objects, in less than 30 minutes.

Reenpred has a versatile track record in practical applications, including:

- A GMV study for **UK DSTL** estimating orbital lifetimes on future populations
- In-house analyses of real re-entry events, such as Tiangong-1 in 2018, Tiangong-2 and BREEZE-M DEB (TANK) in 2019, and Long March 5B in 2021, as part of GMV's participation in **Global Sentinel events** through the Spanish Army.
- Testing data generation for re-entry prediction and on-ground risk assessment, shared with **EU SatCen** for their EU-SST service front-desk.
- Analysis of re-entries at both the Romanian National Operations Centre for SST (**COSST**) and the military German Space Situational Awareness Centre (**GSSAC**, since 2023).

As an end-user product, ***Reenpred*** generates the following products: **orbital lifetime file** (estimated orbital lifetime of all objects in the catalogue), **re-entering objects file** (list of objects with an orbital lifetime smaller than a configurable threshold -e.g. 60 days-), **re-entry data file** (orbital lifetime, re-entry epoch, impact epoch, uncertainty, casualty risk, fatality risk, etc. in the form of a re-entry warning and CCSDS re-entry data messages, RDM), **re-entry trajectory file** (re-entry trajectory, impact location and uncertainty of the parent object and its fragments in XML OEM format), **re-entry impact file** (information on the Earth surface covered by the n-sigma uncertainty associated to the re-entry in XML format), **visibility re-entry events** (start/end times of visibility from each zone of each object), **re-entry report** (pdf report based on a configurable LaTeX template including global and local ground-track plots).

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Figure 1: Example of re-entry warning message

Figure 2: Example of re-entry ephemeris file

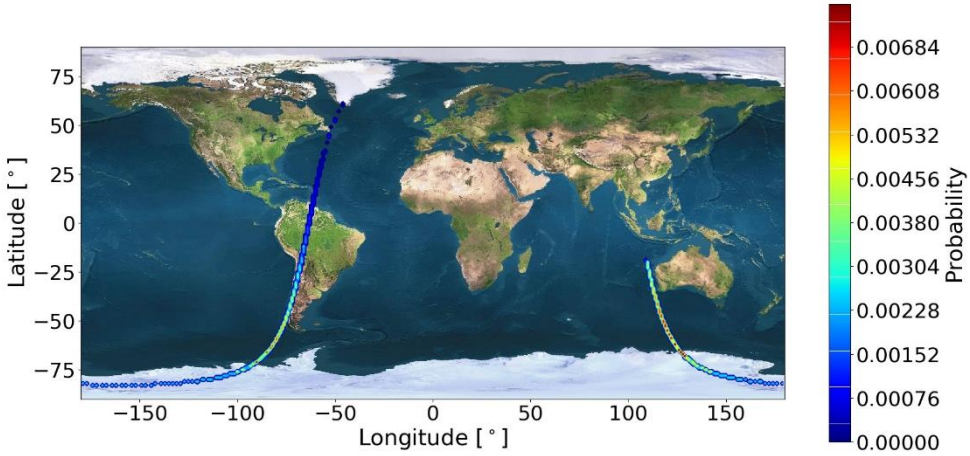

Figure 3: Example of heat map plot generated by ***Reenpred***

The capabilities of ***Reenpred*** COTS are based on GMV's extensive experience in developing other re-entry analysis software, including the development and maintenance of **ESA's Re-entry Prediction System (RPS)** as part of the SSA Program, **CNES's OPERA SW**, designed for **orbital lifetime estimation** using publicly available TLE data, **CNES's DEBRISK & PAMPERO SW**, dedicated to **re-entry analysis**, encompassing fragmentation simulation and assessment, and the **controlled re-entry module T-DEM** within the comprehensive Flight Dynamics System for CNES's Automated Transfer Vehicle (**ATV**).

GMV's experience in the topic includes providing support to the **Flight Dynamics operations, including controlled re-entry**, for all five **ATV** missions, and to the provision of **re-entry service at S3TOC** as part of the Spanish contribution to the **EU-SST support framework**.