

ESA SPACE SITUATIONAL AWARENESS PROGRAMME: RE-ENTRY PREDICTION SYSTEM (RPS) OF THE SPACE SURVEILLANCE AND TRACKING SEGMENT

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ABSTRACT

The overall aim of the Space Situational Awareness (SSA) Programme is to support the European independent utilisation of and access to space for research and/or services. The main objectives of the SST segment of the SSA system are to generate and maintain the catalogue of objects relevant to and required by the services of the SST segment. The SST Re-entry Prediction Subsystem (RPS) predicts the lifetime of objects orbiting the Earth and evaluates the threats that re-entering objects pose on the population and ground assets.

This paper describes the techniques applied to filter the catalogue for potential upcoming re-entry objects and to predict the orbital lifetime, the methods used to simulate the destructive re-entry and, in the case of surviving fragments, the capabilities to assess the risk these present. In addition, the way in which the RPS obtains and utilises orbit uncertainty data is presented. The paper also illustrates how the RPS is embedded into the overall SSA-SST system and explains the user interfaces and plotting capabilities of the RPS.

1. SSA OVERVIEW

1.1. General

The objective of the SSA programme is to support Europe's independent utilisation of, and access to, space through the provision of timely and accurate information and data regarding the space environment, and particularly hazards to infrastructure in orbit and on the ground. Ultimately, this will enable Europe to autonomously detect, predict and assess the risk to life and property due to man-made space debris objects, re-entries, in-orbit explosions and release events, in-orbit collisions, disruption of missions and satellite-based service capabilities, potential impacts of Near-Earth Objects (NEOs), and the effects of space weather

phenomena on space- and ground-based infrastructure.

All of these -potentially catastrophic- phenomena may lead to shut-down or loss of services from space or ground-based assets, or even loss of life. In the event of a disruption to space-based services or supporting infrastructure on the ground, citizens' safety could be significantly affected and the delivery of emergency services by regional, national and European authorities could be considerably impaired.

Any disruption could also seriously affect an enormous range of commercial and civil activities, including commercial land, air and sea travel, maritime navigation, telecommunications, information technology and networks, broadcasting, climate monitoring and weather forecasting, to name but a few.

It is therefore of prime importance to have the ability to detect potential on-orbit collisions, or to alert when and where debris re-enters the Earth's atmosphere. To date, Europe's access to information on what is happening in space has been largely dependent on non-European sources. An example of this is that, in recent years, data needed to trigger mitigating actions regarding potential collisions between European satellites and debris objects have only come through the goodwill of other spacefaring nations. For this and other reasons, Europe needs an autonomous SSA capability.

1.2. SSA Space Surveillance and Tracking

Space Surveillance and Tracking is required to respond to the need to maintain the awareness of the population of man-made space objects. The central aim of SST is to provide an independent ability to acquire prompt and precise information regarding objects orbiting the Earth. Through the SSA-SST programme Europe may acquire its own surveillance and tracking service for several applications, including:

- Launch and early operations (confirmation of the separation of the satellite from the launcher, initial orbit tracking)
- Contingencies (tracking of passive satellites and support to the investigation of in-orbit failures)
- Mission support (object tracking, support for controlled re-entries)
- Collision avoidance (conjunction events detection and tracking)
- Detection and characterisation of in-orbit fragmentations
- Re-entry of risk objects
- Space traffic awareness (tracking and cataloguing space population)
- Identification (identification and trace-back of space objects)
- Characterisation of the sub-catalogue environment (for objects one order of magnitude smaller than catalogue size limit, and for space debris modelling)

The SSA-SST segment intends to provide coverage across all orbital regions up to 2000 km beyond the nominal GEO altitude (LEO, MEO, GTO, Molniya, GEO, etc).

Within the precursor service phase of SSA two analyses systems were implemented: an in-orbit conjunction prediction system and a re-entry prediction system. The latter is covered by this paper and will be presented in the following sections.

2. RPS – REENTRY PREDICTION SYSTEM

The re-entry prediction system (RPS) shall allow an early warning to be given to clients of the system, such as national governments and organisations related to crisis management and traffic safety.

The RPS predicts probable impact zones and identifies affected countries. This prediction and the associated automatic tool chain, including email and NOTAM (Notice to Airmen) notifications, allows for fast and selective information provision to clients responsible for the affected areas.

The provided notification comprises

- the predicted date and time of impact
- date and time of the analysis
- the predicted fatality and casualty probability
- nominal impact location of each surviving fragment
- probability impact area
- list of affected countries
- probability to fall on land
- expected date and time of the next update

The RPS consists of two main subsystems: the Lifetime Prediction System (LPS) and the Re-entry Analysis System (REA). The subcomponents of the LPS

accomplish the following tasks:

- Providing a database of man-made objects with perigee altitude below 2000 km
- Ballistic Parameter Determination (BPD) for objects, for whom the ballistic parameter is unavailable.
- Orbital Lifetime Calculation (OLC) for all objects below 2000 km altitude.
- Risk Object Identification (ROI) to identify those objects that re-enter within a pre-defined period of time.

The subcomponents of the REA perform the following tasks:

- Atmospheric Re-entry Propagation (APRS) of objects, which have been identified by the LPS as re-entering within a close timeframe.
- Risk Assessment (RA) for the objects or fragments thereof which impact the Earth surface.

Furthermore, the RPS comprises components that manage the interaction with the database and a plotting component that is part of the system user interface. All RPS components and their relationship are shown in Fig. 1.

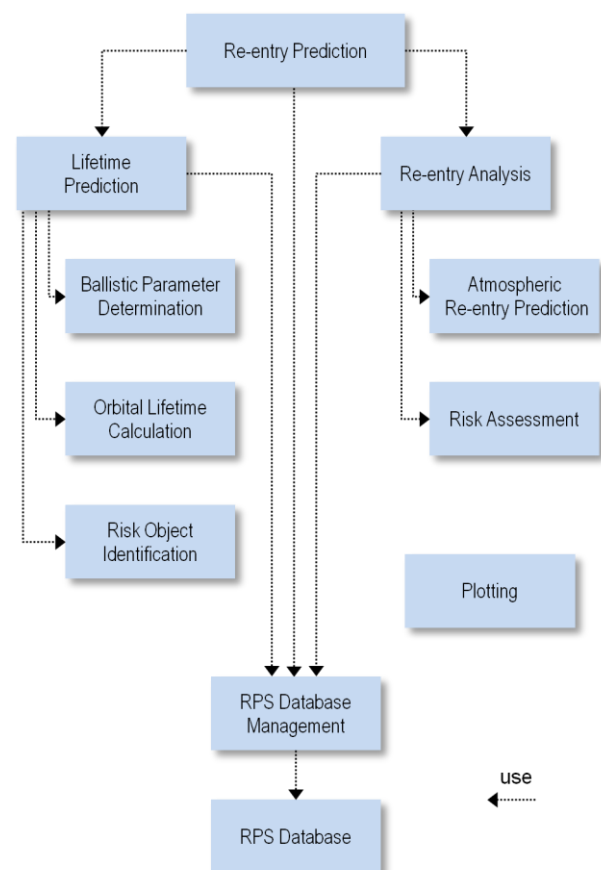


Figure 1: Re-entry Prediction System components overview

2.1. LPS - Lifetime Prediction System

The LPS is responsible for the prediction of the non-atmospheric (>120km altitude) evolution of catalogue object trajectories. Its components are described below.

2.1.1. BPD - Ballistic Parameter Determination

The BPD is responsible for the determination of the ballistic parameter for an object with a perigee altitude below 2000 km. A shooting method is applied to the orbital elements history of the object for which the values of cross-section and mass are not available.

Using the object ID as identifier, the orbital elements history is acquired from the database for the considered object. The orbital element data are used as Keplerian elements. For different propagators different kinds of orbital elements can be chosen. The ORBPRO [1] propagator uses mean orbital elements with semi-major axis, mean motion, eccentricity, inclination, right ascension of ascending node, argument of perigee and mean anomaly. The NAPEOS [3] propagator uses osculating orbital elements with semi-major axis, eccentricity, inclination, right ascension of ascending node, argument of perigee and true anomaly.

These datasets are filtered for data set pairs within the defined shooting interval such that they can be used for the ballistic parameter estimation. For every data pair a ballistic parameter is determined. Subsequently the ballistic parameter of the object is averaged over the determined ballistic parameters of the data pairs.

To determine the ballistic parameter, BPD performs the following steps. First, the objects are filtered for the availability of mass, cross-section and drag coefficient. If these parameters are available, the ballistic parameter is calculated analytically in order to obtain a more realistic orbital lifetime result based on known spacecraft properties. In the case of a missing drag coefficient, the commonly used default value for C_D of 2.2 is assumed.

The drag force is the major influence parameter for the ballistic parameter determination. For this reason the estimation of ballistic parameters for objects with a perigee altitude above 2000 km is not reasonable. In such cases a default value for the ballistic parameter is assumed by the BPD. The shooting algorithm is applied to the objects with the perigee altitude below 2000 km.

For the shooting method a number of n data pairs are filtered from the orbital elements history of the catalogued object. The filter is applied according to the defined minimum shooting interval (time period). The ballistic parameter which is valid for the observed decay of each data pair (two Keplerian sets from two time points) is determined by an iterative calculation by applying the “shooting method”.

Each ‘shooting step’ consists of two orbit propagations from the start epoch of the specific data pair to the target epoch of the data pair (using the corresponding Keplerian state for the start epoch). These two orbit propagations are performed with two different ballistic parameters yielding two different semi-major axes at target epoch.

To obtain an initial value of the ballistic parameter for each interpolation step, a logarithmic interpolation between the results of the preceding ‘shooting step’ is performed. To obtain the two different ballistic parameter values for the next shooting step a simple algebraic expression is used.

These steps are repeated until the difference between the two ballistic coefficients is less than a user defined threshold. After having evaluated all n pairs, the mean value of the resulting ballistic parameters is written to the database.

2.1.2. OLC – Orbital Lifetime Calculation

The purpose of the OLC is to provide lifetime estimates for objects with a perigee altitude below 5000 km. The lifetime is determined by means of different orbit propagators, which are applied in accordance to the accuracy requirements set by the user.

In the first step OLC checks which objects are requested to be considered.

For the considered objects an analysis is performed depending on the lifetime classes (update interval) and the follow up priority if the lifetime has to be updated.

The objects to be updated are scanned if the previous estimated decay date is in the predefined re-entry period according to the follow up priority. If this is the case, they will re-enter in the predefined re-entry period. These objects are skipped to avoid redundant consideration because they will be handled by ROI and if necessary analysed by ARPS where the impact date is determined and the lifetime can be defined with respect to the calculation date. Thus lifetime and decay date are a by-product of ARPS for the re-entering objects.

Objects that have a follow up priority ‘no tracking’ (their perigee altitudes are higher than 5000 km) are omitted as well. The lifetimes of these objects are practically of such a great duration that no re-entry is anticipated in the foreseeable future and thus the forecast of the lifetimes is not reasonable. These objects are only checked by ROI if the perigee altitude dropped below 5000 km for some reason and thus they shall get a new follow up priority and lifetime estimation shall be performed.

For the remaining objects the lifetime estimation is performed by propagating the objects with an

appropriate propagator until they reach the re-entry conditions defined by the user.

The decision about which propagation tool shall be used is made on the previous estimated lifetimes and on the user defined lifetime classes for every object.

The user can define parameters of six lifetime classes, from extremely long lifetime to very short lifetime. For each of these classes the lower lifetime threshold, (e.g. short lifetime => 1 year), an update interval and the propagation method to be applied for this class have to be specified by the user. Furthermore he is able to specify two re-entry periods, for low fidelity and high fidelity monitoring objects, with residual lifetime percentage to be considered as uncertainty and a percentage of residual lifetime to be used as an update interval.

The three methods for the orbit propagation are selectable in the OLC:

- The FLiP propagator [1] is used for the first lifetime estimation if no previous lifetime estimate exists. It is a straight forward analytical propagator with an algorithm based on the King-Hele theory [2]. Drag is the force driving the propagation.
- The ORBPRO [1] propagator applies an incremental analytical propagation with an algorithm based on the King-Hele theory. For the propagation a user defined propagation step dt is used. For each step a supposed lifetime L is defined and compared to the propagation step. If $dt/L > 1$, then the object is decayed. The propagation step dt must be positive and is limited to 10 days based on experience in LASCO [1]. If the object is not decayed, the orbital elements for the new position are calculated.
- NAPEOS [3] is a numerical propagator. The utilized integrators by NAPEOS include an 8th-order Adams-Bashforth / Adams-Moulton prediction-correction method, a fixed step 8th-order Runge-Kutta method and a variable step 7-8th-order Runge-Kutta method.

2.1.3. ROI – Risk Object Identification

The purpose of ROI is the mapping of the follow up priority (low fidelity, high fidelity) to every object in the database.

The perigee altitude is checked for all remaining objects. The risk criteria cause different monitoring levels for an object: no tracking, low fidelity monitoring or high fidelity monitoring. To set up the monitoring level, which is used as a composite filter criterion, different parameters are checked against user defined thresholds:

- ROI screens the objects if the perigee altitude is above 5000 km. The monitoring level for these objects is set to ‘no tracking’. In this manner it is checked periodically whether the perigee altitude of such objects has decreased below 5000 km and a new follow up level definition and lifetime estimation is needed.
- The cross-section and the ballistic parameter of objects with a perigee altitude below 5000 km are checked for crossing the user defined thresholds. If the thresholds are fulfilled, the follow up priority of these objects is adjusted to high fidelity, because they can pose a higher risk on ground during the re-entry. Additionally the objects are checked against entries in a file with user defined hazardous objects, e.g. due to carrying nuclear material. Objects including in the named file get always the follow up priority ‘high fidelity’, regardless of the values for cross-section, mass or ballistic parameter.
- Objects with a perigee altitude below 5000 km that do not fulfil one of the user defined thresholds and that are not in the file defining hazardous objects, get the ‘low fidelity’ monitoring level.

Besides the monitoring level definition, ROI propagates the orbits of objects that will re-enter in the user predefined time periods (low, high fidelity) and that are meant to be handled by ARPS.

First ROI checks which objects have to be considered. For the filtering of the objects of interest, ROI screens all re-entry dates of the considered objects with the high fidelity level, if they are in the user defined high fidelity re-entry period with considered user defined uncertainties. The uncertainties are defined as a percentage of the residual lifetime. For the objects to be considered, the maximum residual lifetime is in the order of the user defined re-entry period. Thus this time period is raised by the defined percentage. Objects found to have a decay date in this re-entry period are considered as re-entering objects.

The same procedure is performed for the considered low fidelity objects applying the low fidelity re-entry period. Using the previously estimated orbital lifetime, the monitoring level and the corresponding residual lifetime percentage for the update interval, the next update date for the object is determined. This update date is compared with the current date, and it is decided whether an update is required.

For those objects, where an update has to be performed, the propagation is done with the most accurate propagator available (NAPEOS) to the starting point of ARPS. The propagation provides the resulting state vector and covariance matrix.

2.2. REA Atmospheric Re-entry Analysis

The REA (Re-entry Analysis System) is the last part in the re-entry prediction chain. It is in charge of propagating the object trajectory during the atmospheric re-entry and of computing the risk figures in case that the object survives the re-entry and impacts the Earth. These tasks are tackled by two separate software modules: the ARPS (Atmospheric Re-entry Prediction System) and the RA (Risk Assessment System).

The ARPS is provided with the initial state and object properties. That data comes from the LPS. It initializes the atmospheric re-entry propagation, propagates the re-entry object dynamic and thermal states and checks for event triggers and performs trigger actions. The output of the ARPS is input for the RA.

2.2.1. ARPS - Atmospheric Re-entry Prediction System component

After an object has been qualified for an atmospheric re-entry by the LPS, its parameters are handed over to the ARPS that propagates the re-entry trajectory till impact or object demise. ARPS follows an object-oriented approach, i.e. the re-entry object is modelled based on predefined primitive shapes. This approach is known from tools like DARS [6] or SESAM from the DRAMA [7] suite. Since in general not much data is available for catalogue objects, the object break-down into primitives is solely based on object mass, ballistic coefficient and object class.

For each object class a principle setup of child objects (fragments) has been defined, based on an analysis of well-known representative objects. This default setup is scaled for each re-entry object to meet the ballistic coefficient and total mass. Fragmentations and explosions are triggered by a set of events. The architecture allows considering more specific input data as soon as it becomes available.

Since a lot of objects have to be propagated within an automatic batch process every night it is not possible to perform a Monte Carlo simulation in order to identify the impact area. Therefore the initial covariance provided by the LPS is propagated for each fragment. The final covariances of impacting fragments define the probability impact area.

Environment Models

The perturbations considered in the atmospheric re-entry comprise the gravitational force by a J2 Earth spherical harmonics (EGM96) model and the aerodynamic drag force. The user can select either the MSISE90 or the NRLMSISE00 atmosphere model for the computation of the aerodynamic force.

Propagator

The integrator used is a Runge-Kutta45 integrator with a user defined maximum step size (output step size). Only the positional but not the rotational state is propagated. The covariance is extrapolated by the state transition matrix which is approximated using finite differences.

Examples of propagated trajectories will be shown in section 2.3.1.

Aerothermal Model

The thermal model is based on a lumped mass object model considering heat transfer and heat radiation. This simplification is linked to the assumption of fast tumbling fragments and homogeneous heating. As a consequence of that assumption also the lift force can be neglected for the propagation of the trajectory.

Heat fluxes are calculated based on formulations by Detra, Kemp & Ridell [4].

Object dimensions and shape management

During melting, the object dimensions are adapted according to the propagated mass. As soon as the wall thickness goes below a critical value, hollow objects are converted into solid bodies with equivalent mass.

Fragmentation Model

The re-entry object fragmentation model follows an object oriented approach in order to meet the performance requirements on the risk analysis. The object properties comprise: mass, shape, dimensions, material. There are three types of possible fragmentation events:

- **Explosion:** an explosion is triggered for re-entry objects of type ROCKETBODY since these may contain remaining fuel. The explosion is triggered when an altitude of 78 km is reached. The explosion model is based on the EVOLVE 4 explosion model by NASA [5]. The characteristics of the newly created fragments follow a statistical distribution.
- **Pre-defined fragmentation:** this fragmentation event is used for objects of type PAYLOAD and is based on a pre-defined fragments definition of a typical payload spacecraft. The mass and dimensions of the pre-defined fragments are scaled to fit the re-entry object mass and dimensions.
- **Automatic fragmentation:** this trigger action causes that a fragment is split into two child fragments.

The available trigger conditions for these actions are altitude, temperature, percentage of melted material, exceeded dynamic load and exceeded dynamic pressure. Multiple trigger conditions can be defined for each predefined fragment and/or the parent object and at each time step all of them are checked.

2.2.2. RA - Risk Assessment component

The RA computes the impact risk figures of a re-entry object which produces impacts on the Earth surface and calculates the contour of the probability impact area.

The output of ARPS, namely the final states (position velocity, covariance matrix, mass, dimensions) of each fragment, is input to the RA.

The eigenvalues of the covariance matrix are used to generate the probability impact area of an individual fragment (ellipse-shaped due to multivariate normal distribution). The total impact probability density is calculated assuming no correlation between the individual impact areas (see Fig. 2). Afterwards, the correct threshold of the probability density function PD is calculated in an iterative process such that the total probability impact area PIA (red-dotted area in Fig. 2) corresponds to the impact probability specified by the user (in terms of sigma multiples). It has to be noted that with this approach the PIA is not necessarily one contiguous area but can be divided into several separate areas. Further it might happen that a nominal impact point is not located within the PIA. This occurs when the probability density function of the impacting fragment is rather flat with a low peak.

The total probability density function is used to calculate the impact probability for each country, the probability to fall on land and – using extrapolated GPWv3 population density data [8] – casualty and fatality probability. All these operations are performed on an Earth grid with 2.5 arc seconds resolution. A user-defined probability threshold defines which countries will be listed in the re-entry message.

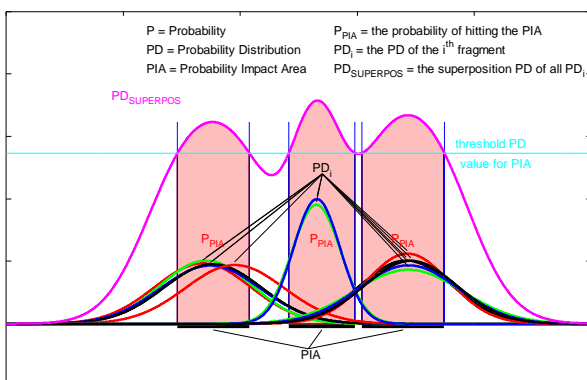


Figure 2. Schematic illustration to the computation of the probability impact area.

2.3. User Interfaces

The LPS is based on a number of available orbit propagators and tools written in FORTRAN, while the REA system is based on applications written in C++. To access these systems and tools, the general strategy is to establish wrappers programmed in Java around them,

enabling integration into the Space Surveillance and Tracking Segment (SST). The integration and coordination of these components is performed via the Java Enterprise Edition 6 technology stack, using the Java Connector Architecture (JCA). For both the LPS and the REA a so-called connector is established. Each connector is responsible for writing the appropriate input files, triggering the executables and parsing the results for the applications included in the subsystems. The use of these connectors enables the specification conform integration of the non-Java components into an enterprise application. Such an application is not only used for the coordination of the systems, but also for the provision of an interface to access these systems.

The RPS is intended to be used as a system, managed and accessible via a Web Based Front End (WBF) and via a standalone Human Machine Interface. Both front ends are not restricted to the RPS but cover also other aspects like conjunction analysis, which are not covered by this paper.

Two different user roles are foreseen: the client user and the service manager. The client user can view re-entry analysis results created by an automatic run (service) or he can provide his own orbit data for selected objects (as CCSDS Orbit Parameter Messages). For both cases the user can view the results in terms of reports, x-y plots and map plots. Automatic notifications about predicted re-entries are sent to the user via email. Based on the user's preference setting only impacts affecting his country or all predicted impacts will be reported. Via a dedicated page he can observe all analyses performed within the last 7 days, whereas impact events are specially marked.

The service manager user controls the automatically running analyses. He can specify several scenarios that are executed with a specified frequency. Each scenario might contain all objects or just a subset (e.g. to monitor high-risk objects more frequently). He has an overview of the high risk objects via an alerts page and can of course also view the analysis results for an individual object. The service manager user can further access the system via the stand-alone Human Machine Interface.

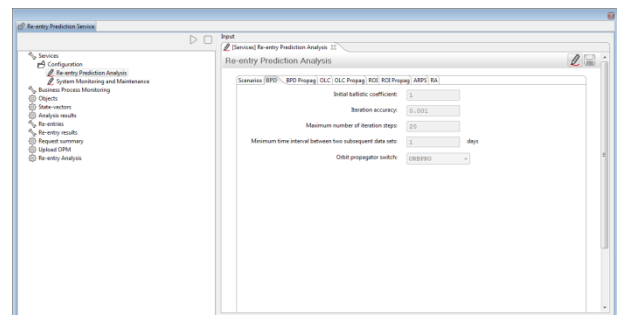


Figure 3. Stand-alone HMI showing configuration parameters for the BPD.

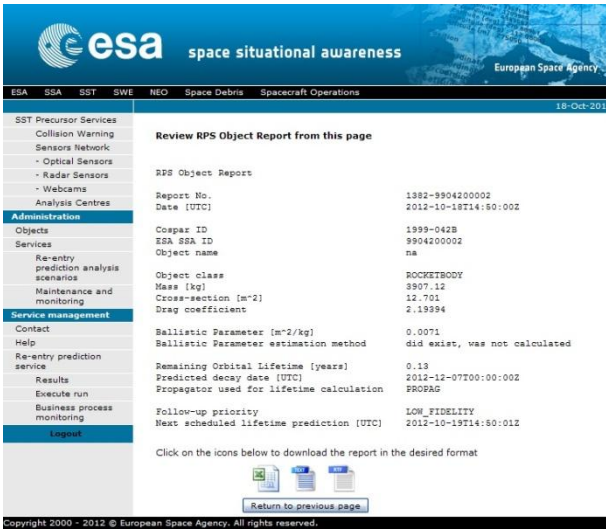


Figure 4: WBFE showing a report for an object selected by the user

2.3.1. Plotting Tool

As described above, the analysis results produced by ARPS and RA can be visualized in the WBFE and in the HMI. The following plots are available to the user:

- 2D plots over time of the altitude, kinetic energy and the covariance matrix elements (see Fig. 5)
- 2D map plot of the ground track of the object and its fragment with an indication of events along the trajectory (see Fig. 7).
- 3D map plots of the object and fragments trajectories with an indication of events along the trajectory (see Fig. 6).

Each plot type provides zooming and panning capabilities and can be exported to an image file in PNG or JPEG format.

The map plots support GIS (Graphical Information System) layer support, i.e. the user can upload auxiliary data that is displayed along with the trajectory data (e.g. country borders, population density data, cities, roads, etc.). The plots support two popular formats: ESRI Shapefile [9] and GeoTIFF [10]. While the ESRI Shapefile is mainly used to provide vectorial data, GeoTIFF supports only rasterized maps.

Frequently needed GIS data like country borders are already available and does not need to be uploaded by the client.

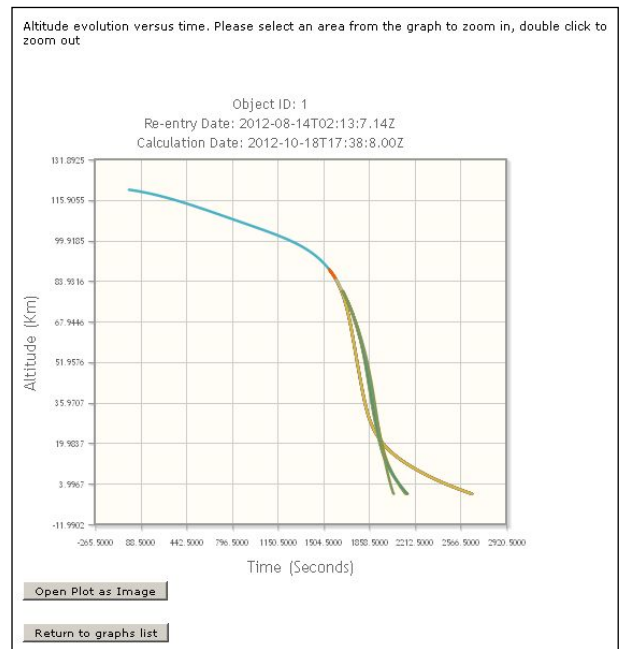


Figure 5: X-Y plot showing the altitude evolution vs. time for each fragment

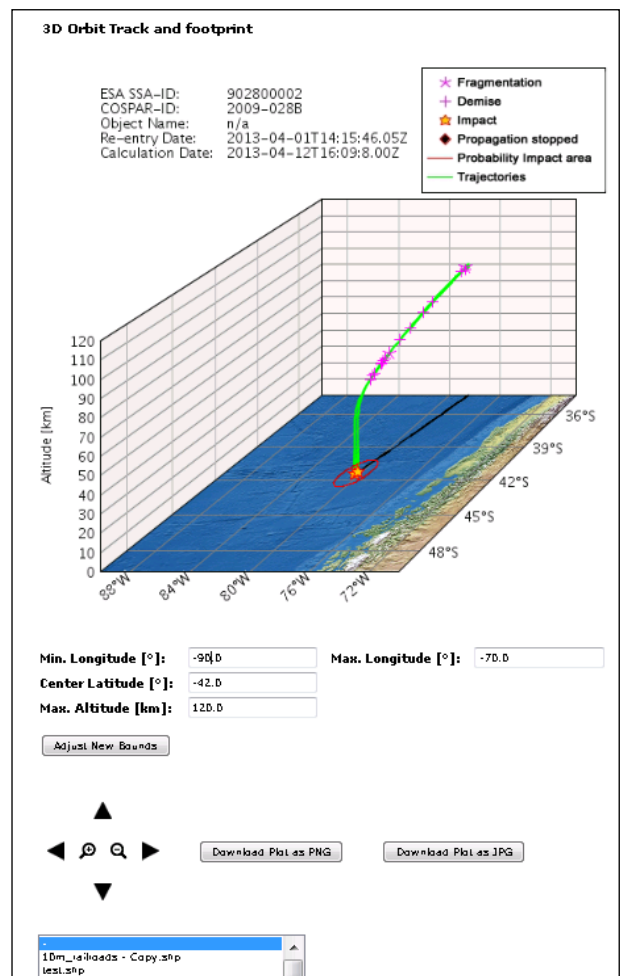


Figure 6: 3D map plot showing fragmentation demise and impact points

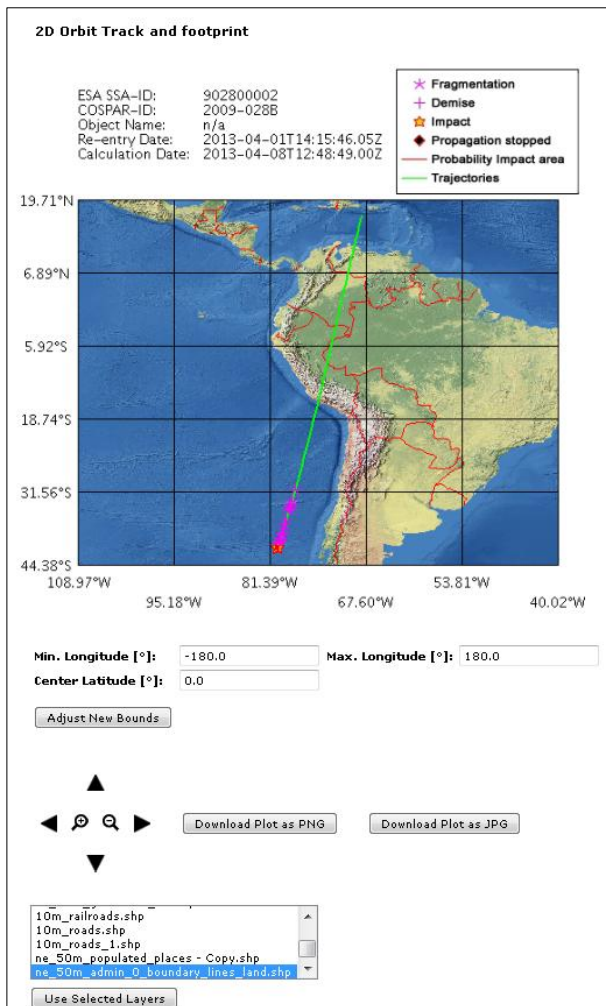


Figure 7: 2D map plot with country border GIS layer

3. CONCLUSIONS

The presented capabilities of the SSA-SST re-entry prediction service allow a fast and automatic notification in case that a predicted re-entry might cause a threat. Through an easily accessible web-based front end consecutive observations and updated trajectory data can be either calculated on-demand in the system or injected by clients themselves. This allows for a rapid response to the changing evolution of a re-entry event and enables for accurate space situational awareness. This level of current knowledge is mandatory for the effective deployment of countermeasures such as civil protection emergency protocols or (air)traffic rerouting.

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