IAC-22,A6,IP,24,x73624

A re-entry analysis software module for Space Surveillance and Tracking operations

R. Cipollone[a]*, M. F. Montaruli[b], Niccolò Faraco[c] , Pierluigi Di Lizia[d], Mauro Massari[e] , Andrea De Vittori[f] , Moreno Peroni[g] , Alessandro Panico[h] Andrea Cecchini[i]

[a] *Politecnico di Milano, Department of Aerospace Science and Technology, Via La Masa 34, 20156 Milano MI*, *Italy*
riccardo.cipollone@polimi.it
[b] *Politecnico di Milano, Department of Aerospace Science and Technology, Via La Masa 34, 20156 Milano MI*, *Italy*
marcofelice.montaruli@polimi.it
[c] *Politecnico di Milano, Department of Aerospace Science and Technology, Via La Masa 34, 20156 Milano MI*, *Italy*
niccolo.faraco@polimi.it
[d] *Politecnico di Milano, Department of Aerospace Science and Technology, Via La Masa 34, 20156 Milano MI*, *Italy*
pierluigi.dilizia@polimi.it
[e] *Politecnico di Milano, Department of Aerospace Science and Technology, Via La Masa 34, 20156 Milano MI*, *Italy*
mauro.massari@polimi.it
[f] *Politecnico di Milano, Department of Aerospace Science and Technology, Via La Masa 34, 20156 Milano MI, Italy*
andrea.devittori@polimi.it
[g] *Aeronautica Militare - Reparto Sperimentale di Volo Via Pratica di Mare 45, 00071, Pomezia RM, Italy*
moreno.peroni@aeronautica.difesa.it
[h] *Aeronautica Militare - Reparto Sperimentale di Volo Via Pratica di Mare 45, 00071, Pomezia RM, Italy*
alessandro1.panico@aeronautica.difesa.it
[i] *Aeronautica Militare - Reparto Sperimentale di Volo Via Pratica di Mare 45, 00071, Pomezia RM, Italy*
andrea1.cecchini@aeronautica.difesa.it

* Corresponding Author

Abstract

Space Surveillance and Tracking (SST) is growing more and more important in the Space operations and mission analysis field, given how much the crowded environment building up near Earth can hamper them. Italy is involved in SST operations with collaborations both within and outside the EU. The Italian Space Operation Centre (ISOC) has recently upgraded its systems to the ISOC 2.0 Suite, an integrated platform providing multiple functions and services in the SST domain. The platform is web-based, giving users the ability to connect and use the system both locally and remotely via web browser. The software has been designed and implemented through partnerships involving industry and academia. Among the wide range of SST-related activities, one of the most concerning is the controlled or uncontrolled atmospheric re-entry of space objects (SO). The analysis and monitoring of such events prove crucial to reacting as promptly as possible when the need arises. The present work describes the re-entry analysis module developed for ISOC 2.0 Suite thanks to a collaboration involving the Italian Air Force, Leonardo and Politecnico di Milano. It consists in a tool performing long-term high-fidelity propagations of SOs, re-entry assessment and processing. Its output is structured as a detailed report involving several pieces of information. Firstly, the nominal re-entry coordinates are provided and enriched with corrections based on the modulation of the target cross-area used to fit a given time delay or advance through a zero-finding process. The software also supplies a ground track in the form of a band enclosing the offset from the nominal footprint. Entry and exit times related to areas of interest and national borders are computed too as part of the report for a given time window about nominal re-entry epoch. Besides, a ballistic coefficient estimation is performed, based on the latest orbital data files available to counterbalance dynamical model inconsistencies. A filtering process is embedded in this step not to let outliers affect the quality of the estimate. Finally, a statistical break-up model based on thermal analysis and typical SO properties is included to properly account for the last phase of the event resulting in increased robustness. This module has been tested against both synthetic and real past re-entry events, giving reliable results and predictions.

Keywords: re-entry, SST, break-up model, high-fidelity propagation

Nomenclature

- $\boldsymbol{J}$ [s]: residual function
- $\boldsymbol{T_n}$ [s]: nominal re-entry epoch
- $\boldsymbol{\Delta t}$ [s]: input time shift
- $\mathbf{T_s}$ [s]: synthetic re-entry epoch
- $\boldsymbol{\phi_x}$ [km, km/s]: propagation flow
- $\boldsymbol{t_0}$ [s]: initial epoch
- $\boldsymbol{x_0}$ [km, km/s]: initial orbital state

- $\boldsymbol{h_d}$ [km]: decay altitude
- $\boldsymbol{A2M}$ [m^2/kg]: area-to-mass ratio
- $\boldsymbol{\phi}$ [deg]: longitude
- $\boldsymbol{\lambda}$ [deg]: latitude
- $\mathbf{r}$ [km]: target position
- $\mathbf{R_e}$ [km]: Earth radius
- $h_\mathbf{e}$ [km]: target altitude wrt Earth
- $\boldsymbol{\beta}$ [deg]: footprint slope angle

Acronyms/Abbreviations

- RSO: Resident Space Object
- SST: Space Surveillance and Tracking
- ESA: European Space Agency
- SSA: Space Situational Awareness
- EUSST: European Space Surveillance and Tracking
- ASI: Agenzia Spaziale Italiana (Italian Space Agency)
- INAF: Istituto Nazionale Di Astrofisica (National Institute of Astrophysics)
- AM: Aeronautica Militare (Italian Air Force)
- ISOC: Italian Space Operation Centre
- RE: Re-entry
- FG: Fragmentation
- CA: Conjunction Analysis

1. Introduction

The last decades have been characterized by a significant increase in space activities spanning every orbital regime, both for scientific and commercial purposes [1]. This trend has caused Resident Space Objects (RSOs) population management and monitoring to become a progressively growing concern for the Space technology sector, due to its implications and costs on the design and maintenance phases of new missions and operations. Casualty risk is involved as well: a higher number of space objects leads to a higher possibility of re-entry events and, among those, uncontrolled ones involving massive enough objects can result in a threat to be promptly addressed. The Space Surveillance and Tracking (SST) field deals with a range of tasks aimed at granting continuous surveillance on the space object population, exploiting sensor networks, and maintaining catalogues filled with every known object together with its updated orbit. For this purpose, an international commitment is currently taking place. Europe deals with this topic through two programmes: the European Space Agency (ESA) Space Situational Awareness (SSA) programme and the European Space Surveillance and Tracking (EUSST) framework. The latter gathers European national agencies and institutions and focuses on the following services: conjunction analysis, fragmentation analysis and re-entry prediction. These tasks exploit measurements obtained through ground-based sensors, including optical telescopes (acquiring highly accurate angular track), radars (providing range, doppler shift or both measurements in addition to angles) and lasers (employed for their extremely precise range measurements).

Italy is involved in EUSST programme through Italian Space Agency (ASI), Astrophysics National Institute (INAF) and Italian Airforce (AM) and oversees re-entry and fragmentation services. Several sensors (both radar and optical) across the country are operated with this purpose and assisted by continuously evolving software tools and methods to efficiently process measurements ([2],[3]). For this reason, efficient and reliable tools shall be designed to process observation data. Within this framework, the Italian SST Operational Centre (ISOC) has recently upgraded its system to ISOC Suite, an integrated platform providing multiple functions and services in the SST domain. It is a web-based platform giving users the ability to connect and use the system both locally and remotely. The software has been designed and implemented in partnership with industry and academia. The present work describes the re-entry analysis module developed for the ISOC Suite thanks to a collaboration involving the Italian Air Force, Leonardo Company and Politecnico di Milano. After the definition of the software architecture, its prototypal version has been developed and then translated to C++ language to be used in the operational environment, granting the highest performances in terms of computational times.

The main features developed to provide a meaningful analysis of a target re-entry phase start with its ballistic coefficient estimate, based on the last orbital data collected and robust to outliers, to include every unmodeled contribution to the dynamics in the prediction. The actual core of the tool is instead composed of an adaptive prediction of the target trajectory, computed by means of high-fidelity propagation, break-up simulation and the possibility to fit a given delay or anticipation by using area-to-mass ratio (A2M) as tuning parameter. Further post-processing is then performed to provide footprint, intersection epochs with chosen areas of interest and casualty expectancy associated with the predicted impact area. These data are finally organized to generate a re-entry report that can be used as a basis to obtain a first overview of the event.

The objective of this work is to present the software for re-entry analysis embedded in ISOC, by assessing its first results. The paper is organized as follows. First, an overview of the module is provided, and the mathematical theory of the process is discussed. Then a numerical analysis based on an operational case scenario is carried out to validate the tool.

1.1 Italian SST operation centre

ISOC was originally established in 2014 and operated by the military personnel of the Flight Test Wing of the

Italian Air Force. Currently, the operational activities are led by the Air and Space Operations Command, whereas the Flight Test Wing is responsible for Research and Development tasks. The ISOC Suite is a complex system that was originally developed to support Space Surveillance and Tracking tasks, but it is currently evolving towards a broader awareness of the space scenario, to enhance the national security for both civil and military applications. ISOC is also included in the EUSST framework, supporting the service listed below:

- Re-entry (RE): prime responsible for the analysis of uncontrolled re-entry in low atmosphere for large and dangerous objects.
- Fragmentation (FG): prime responsible for the analysis of in-orbit fragmentation as consequence of satellite break-ups or collisions.

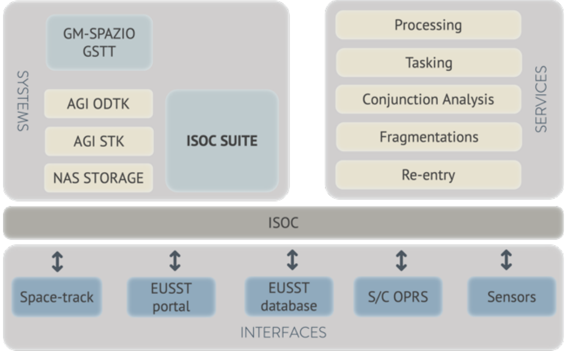

Fig. 1. ISOC comprehensive architecture

ISOC Suite is used to support the above-mentioned services, whose high-level architecture is represented in Fig. 1.

The main inputs of the suite are provided by national sensors, consortium partners observations, European observation catalogue (DCED) along with available public sources. The inner part of the system is based on commercial on the shelf (COTS) and proprietary software. The system output are the services shown in the right part of Fig. 1.

The more specific workflow depicted in Fig.2 represents the actual re-entry analysis module architecture as described in detail in the next sections.

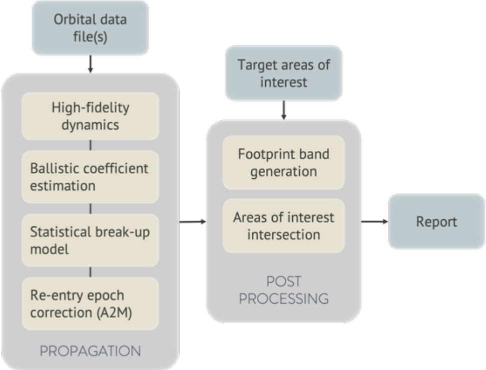

Fig.2. Re-entry module architecture scheme

2. Software architecture and methods

In this section, the architecture of the developed software is discussed in detail. It is built as a series of consecutive simple steps, addressing every piece of information included in the re-entry report, which is the final output of the software.

2.1 Pre-processing

The first step consists in input parsing and pre-processing. Given an input orbital data file (or data file history), the software extracts all the parameters needed to perform a high-fidelity propagation. An in-house developed propagator [4] has been used to carry out the computation coming with this step. The embedded dynamic model includes the following orbital perturbations [5]: atmospheric drag, gravitational harmonics, solid and oceanic tides, third-body perturbation, Solar radiation pressure, albedo, and winds. In order to obtain a reliable drag contribution, a space weather file can be provided as input while the object A2M can either be directly given as input to the propagation or included as part of a ballistic coefficient by means of an estimation process exploiting the latest TLEs associated with the target.

This latter computation is based on the approach proposed by Gondelach et al. [6]. Given two TLEs, the trajectory of the object is propagated from the initial conditions extracted from the older TLE to the epoch of the most recent one, using the secant method to iteratively update the A2M ratio so to match the final conditions expressed in the last TLE. Given the uneven accuracy of the TLEs, the user is also given the option to use more than two TLEs. In such a case, the algorithm estimates the ballistic coefficient over all the possible couples and gives in output the median of the computed values. For the same reason, an additional external module is also provided to get rid of the outliers in the orbital data history. The filter is roughly based on the work by Lidtke et al. [7].

2.2 Trajectory generation

The standard propagation scenario consists in an initial time window of 30 days, used as the default monitoring horizon so to understand if the target is going to re-enter by trespassing a threshold altitude below which the propagation routine stops giving place to the processing phase. Once the nominal re-entry trajectory is computed, in case more flexibility on the actual epoch of impact is needed in the last phases, a root-finding process over the object A2M has been devised to fit a given delay or anticipation. The zero-finding framework is set by selecting a shorter time span that can be either given as input or left as the default value, used to define the arc from the last nominal time instant on which the trajectory modifications will occur. A propagation over this interval is performed iterating on different values of A2M to fit a given delay in time. The scalar function is thus defined as:

$$\begin{aligned} &J(A2M) = 0 \\ &J = [T_n + \Delta t - T_s(\phi_x(t_0, \mathbf{x}_0, h_d, A2M))]^2 \end{aligned} \tag{1}$$

Where $\mathrm{T_n}$ represents the nominal re-entry epoch, Δt is the target time delay or anticipation while $\mathrm{T_s}$ is the re-entry epoch computed as output of the propagation flow ϕ_x, given initial time t_0, state x_0 and decay altitude h_d, with $A2M$ as the only free variable. Both nominal and shifted trajectory are saved to be used during post-processing.

A further level of modelling is embedded in the trajectory generation by adding a statistical break-up model based on the target properties and a first thermal analysis.

The algorithm is inspired by the work of Frank et al [8], which relies on a series of subsequent propagations and an approximate model of the object as a set of basic components. Once the object is in its last descent phase, the propagation is stopped at a user-specified altitude and resumed thereafter using a new dynamical model which includes equations for the evaluation of the temperature variation and mass ablation. In this phase, the object is modelled as a lumped mass with relevant properties. Once the melting temperature of the material is reached, the structure of the object is considered to be suffering a failure and the elements that compose the object are released and continue their descent on independent trajectories. If an object reaches its melting temperature before hitting the ground, the ablation percentage is evaluated at the end of the propagation and used to compute the number of fragments to be considered as the result of the deterioration of the element. The trajectories of these fragments are then propagated from the altitude at which the parent element reached the melting temperature to the ground, in order to evaluate whether or not they undergo a complete demise during the re-entry phase. The complete evolution of the last re-entry phase and break-up is evaluated multiple times in a Monte Carlo simulation, randomly selecting, for each run, the initial temperature distribution of the object and the properties of the element's materials from suited probability distributions. Relevant results like the coordinates of the impact, the velocity and the residual mass of the surviving fragments are saved for each simulation. From these, useful information for the re-entry report can be computed such as the estimated Casualty Expectancy (CE) linked to the event.

2.3 Post-processing

The first post-processing step consists in the generation of the footprint corresponding to the generated trajectory. Given a time series of orbital states associated with the target, cartesian coordinates are converted into latitude and longitude to define the ground-track:

$$\begin{aligned} &\phi = tan^{-1}(r_y/r_x) \\ &\lambda = sin^{-1}(r_z/||r||) \end{aligned} \tag{2}$$

Where ϕ stands for the longitude, λ is the latitude and $\boldsymbol{r} = [r_x, r_y, r_z]$ represents the target Earth-Centred Earth-Fixed (ECEF) position vector. The inverse tangent function used for this step obviously allows for correct quadrant choice and $r_x = 0$ support.

Once the nominal footprint is computed, a band is defined by choosing a shift in *km* corresponding to the arc length from the nominal ground-track on the Earth surface. In order to convert this shift into an angular one, a local spherical approximation is performed:

$$\begin{aligned} &R_e = ||\mathbf{r}|| - h_e \\ &\Delta\theta = \frac{\Delta l}{R_e} \\ &\Delta\lambda = \Delta\theta\, sin(\beta) \\ &\Delta\phi = \Delta\theta\, cos(\beta) \end{aligned} \tag{3}$$

R_e is Earth local radius derived from the computed trajectory, Δl is the input shift in *km* while $\Delta\lambda$ and $\Delta\phi$ are the projection on latitude and longitude of the angular shift $\Delta\theta$ (converted to deg). β represents the trajectory slope angle in the ϕ, λ space.

These two last quantities are then added and subtracted to the nominal footprint to generate the above-mentioned band. Moreover, as a further information to be filled in the report, the ascending or descending direction of the object at re-entry epoch is derived from the slope sign related to the footprint.

The following step concerns the computation of the trajectory intersection with areas of interest. Custom ones can be given as input as *xml* files, in case of simple spans of latitude and longitude, or as *shape* files when national or international borders have to be monitored. Once data are extracted as a series of geodetic coordinates, intersection are computed using a polygon intersection algorithm. This step gives geometrical information only, so indices have to be used to detect the epochs at which intersections occur: they are computed by verifying which footprint segment contains each intersection point. The standard polygon intersection algorithm employed for this application (Matlab *polyxpoly*) considers the two coordinates' series as closed, while only the area of interest is a closed shape. As a consequence, false intersections are detected due to this linking between the two ends of each footprint arc. A filtering step is performed to cope with this issue, by enforcing both positive time difference and longitude step below a certain threshold (derived from the one chosen in the propagation step). A further issue is caused by areas complex morphology and integration sampling: multiple intersections can be in fact associated with the same trajectory segment. This is addressed by means of up-sampling the affected segments halving the original sampling step and linearly interpolating in time to preserve the corresponding epoch information. Once multiple intersections are no longer present in a single segment, the actual intersection epoch computation can take place. This is performed by linearly interpolating each target segment:

$$T_i = T_1 + (\phi_i - \phi_1)\,\frac{T_2 - T_1}{\phi - \phi_1} \qquad (4)$$

Where T_i and ϕ_i are respectively the intersection epoch and longitude, T_1 and T_2 are the epochs associated with the selected segment while ϕ_1 and ϕ_2 represent the boundary longitude coordinates of the segment.
The last step consists in the distinction between entry and exit intersection epoch. This is easily achieved with Matlab *inpolygon* function verifying that a given point is inside or outside a polygon, giving a Boolean value as output. Every entry segment is then associated with a sequence of $[0, 1]$ while every exit one corresponds to the opposite $[1, 0]$. Segments with $[0, 0]$ or $[1, 1]$ are completely inside or outside the target polygon.

3. Testing and results

Software validation involves the real case of CZ-5B rocket body uncontrolled re-entry (ID 45601), orbiting between 150 and 350 km altitude, occurred in May 2020. The analysis starts with the propagation of a given TLE belonging to the target (0.75 days before impact) with the high-fidelity orbit propagator mentioned in section 2.1, to obtain the nominal re-entry state and epoch:

$\boldsymbol{x}_g$ *(km, km/s) = 1.0e+03 ·*

-3.5602
-3.3261
-4.2249
0.0050
-0.0054
0.0002

t_g: *2020 MAY 08 05:25:42.391*

Trajectory sampling density can be tuned according to user needs, whether a finer resolution is required for the post-processing phase or responsiveness is the focus of the application.

By imposing a time shift of *80 min (4800 s)* on the re-entry epoch, the iterative zero-finding process leads to the modified re-entry state and epoch:

$\boldsymbol{x}_{g,m}$ *(km, km/s) = 1.0e+03 ·*

-3.5602
-3.3261
-4.2249
0.0050
-0.0054
0.0002

$t_{g,m}$: *2020 MAY 08 06:45:42.394*

The difference between the two dates turns out to be *4800.0027 s*, proving that convergence to the right solution has been reached.

A slightly different trajectory computation has been set up for the break-up model demonstration. Since the nominal re-entry trajectory predicts an impact site lying on the ocean (associated with a null CE), in order to validate this specific module, the physical parameters of the satellite have been manually tuned to make the re-entry happen on land. In this way the computation of a positive Casualty Expectancy value, performed in conjunction with a provided population density map, is justified.

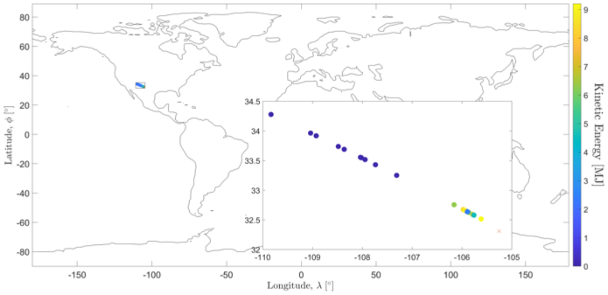

Fig. 3. Fragments impact points distribution example from the break-up simulation module.

Fig. 3 provides a graphical example of the output obtained from the break-up simulation during the re-entry phase, reporting the distribution of the impact points of the fragments on ground, as well as, among the other options, the energy associated with the event. As we can see, less energetic fragments are usually associated with greater A2M ratio and fall to the ground earlier with respect to the nominal re-entry of the point-mass model. More energetic fragments, instead, follow the nominal trajectory more closely.

As for the post-processing phase, some plots are shown to verify the goodness of the results. In Fig. 4, the footprint band generation is displayed, the red line depicts the nominal one, derived from the trajectory, while the blue ones correspond to the band boundaries, obtained by shifting the nominal ground-track by a default arc value of *100 km*.

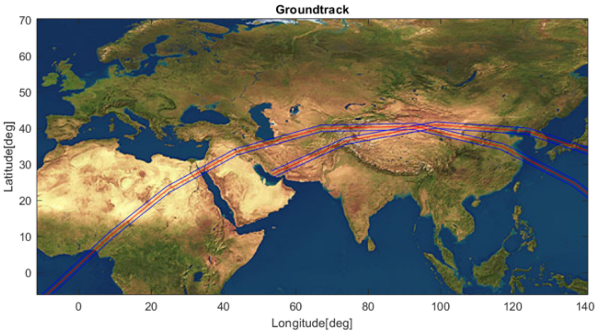

Fig. 4. Footprint band plot example for object CZ-5B. The blue lines represent the boundaries, while the central red one is associated with the nominal trajectory.

As for the intersection detection with areas of interest, two cases are reported. In Fig. 5, the first one consists in a simple "rectangular" area chosen by selecting ranges of latitude and longitude. The cyan circles represent the entry points while magenta is associated with the exit ones. The different colours used for the object trajectory are due to the multiple ground-track segments analysed.

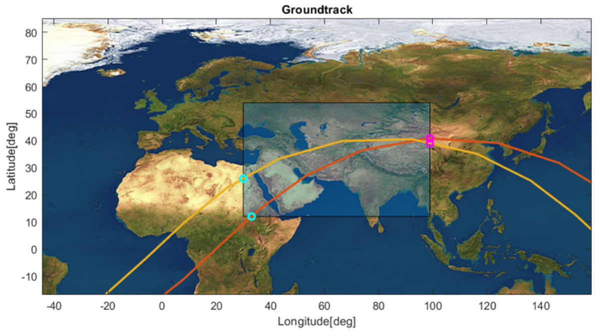

Fig. 5. Intersection points with an example of rectangular area of interest.

Fig. 6 shows an example of part of Greece national borders with the corresponding intersections. This case has been specifically chosen for its complex morphology, giving place to multiple intersections included in the same segment as an example of how effective the lightweight up-sampling of the trajectory can lead to an increased resolution.

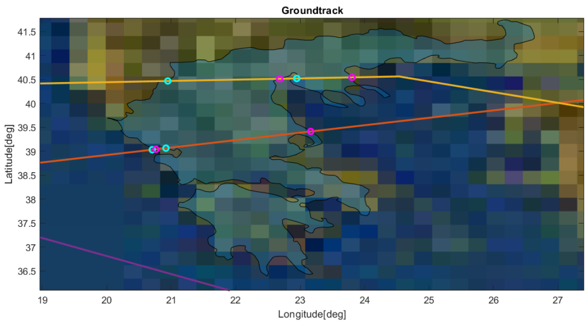

Fig. 6. Intersection points derived from an example shape file associated with a Greece borders.

4. Conclusions

This paper presented a re-entry analysis tool aimed at assisting an operation centre with a comprehensive overview of the event, from objects of interest trajectory computation until impact, through a high-fidelity propagator embedding a data-derived ballistic coefficient estimate and a statistical break-up model based on target properties and thermal status, to the generation of a report including impact epoch correction through A2M tuning, footprint plot and intersection points and epochs with national borders and/or specific areas. The results obtained from a real re-entry scenario have proven to be consistent and their reliability have been deemed compatible with the application. Future events will be surely used as further test bench to corroborate these first outcomes.

Acknowledgements

The authors are grateful to Leonardo Company for the collaboration in the re-entry tool development and testing.

References

[1] ESA Space Debris Office. ESA's Annual Space Environment Report, 27 May 2021. https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

[2] M.F. Montaruli, G. Purpura, R. Cipollone, A. De Vittori, L. Facchini, P. Di Lizia, M. Massari, M. Peroni, A. Panico, A. Cecchini, M. Rigamonti, A software suite for orbit determination in Space Surveillance and Tracking applications, 9th European Conference for Aeronautics and Aerospace Sciences (EUCASS) proceedings, Lille, France, June 2022

[3] M.F. Montaruli, L. Facchini, P. Di Lizia, M. Massari, G. Pupillo, G. Bianchi, G. Naldi, Adaptive track estimation on a radar array system for space surveillance, Acta Astronautica, Volume 198, 2022, Pages 111-123,

ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2022.05.051

[4] Howard D. Curtis. Chapter 3 - Orbital Position as a Function of Time. Howard D. Curtis, editor, Orbital Mechanics for Engineering Students (Third Edition), pages 145-186. Butterworth-Heinemann, Boston, third edition edition, 2014

[5] Howard D. Curtis. Chapter 12 - Introduction to Orbital Perturbations. In Howard D. Curtis, editor, Orbital Mechanics for Engineering Students (Third Edition), pages 651-720. Butterworth-Ileinemann, Boston, third edition edition, 2014

[6] Gondelach, David J., Roberto Armellin, and Aleksander A. Lidtke. "Ballistic coefficient estimation for reentry prediction of rocket bodies in eccentric orbits based on TLE data." Mathematical Problems in Engineering 2017 (2017).

[7] Lidtke, Aleksander A., et al. "Processing two-line element sets to facilitate re-entry prediction of spent rocket bodies from geostationary transfer orbit." 6th International Conference on Astrodynamics Tools and Techniques. 2016.

[8] Frank, Michael V., Michael A. Weaver, and Richard L. Baker. "A probabilistic paradigm for spacecraft random re-entry disassembly." Reliability Engineering & System Safety 90.2-3 (2005): 148-161.