

Preparing for Potential Closure of European Airspaces due to Re-entering Space Objects

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Abstract—The risk of collision between uncontrolled re-entering space debris and aircraft is increasing due to both ever-growing number of airborne flights and of orbiting bodies (and relevant re-entries). National and international authorities need to balance safety and economic impact of adopted measures should a re-entry event be announced, usually on short notice. We employ hourly and daily spatial flight densities calculated from trajectories as recorded by EUROCONTROL’s Network Manager and binned with the Uber H3 geospatial indexing system.

Impact risk probabilities are then calculated based on previous theoretical work. This work enhances the model by employing using actual flown flight trajectories as a basis for time-varying flight densities rather than relying on proxies such as the population density or ADS-B/Mode S message counts. These densities combined with a buffered area along the eventual path of re-entry, can provide mid-air impact probabilities to authorities as an aid for deciding on safety measures such as airspace closures and/or re-routings.

I. INTRODUCTION

With forecasts predicting a steadily growing number of flights, see Fig. 1, and the modern race to commercialise space call for a re-evaluation of the risk of collision and casualties due to uncontrolled debris re-entries. Overseeing authorities need methodologies and tools to assess which safety measures are the most adequate to minimize casualties and economic impact.

Surging number of flights in Europe [1] and in the world, but more importantly under development/deployment mega-constellations of satellites in Low Earth Orbit (LEO), such as already active Starlink and OneWeb or planned ones like Kuiper, Starshield, Xingwang et al. will add thousand of orbiting objects with a short operational life. Some of these will inevitably re-enter the Earth’s atmosphere in an uncontrolled manner, cfr. Table I.

This paper develops a practical and straightforward pipeline to rapidly assess the risk from uncontrolled re-entry of space debris for the European region. Apart from the general risk assessment of potential re-entries, we analyse a soon to occur re-entry of debris from a 1972 failed USSR mission to Venus.

II. METHOD

We follow the same mathematical approach of [2], [3] but instead of approximating flight density with population density [2] or aircraft transponder data [3], we use flown trajectories.

We base our hourly flight density estimation on flown Instrument Flight Rules (IFR) trajectories as recorded by

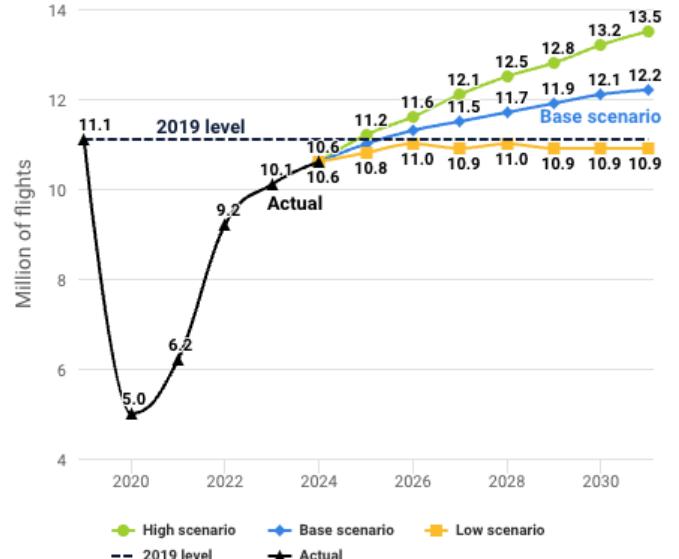


Fig. 1: EUROCONTROL 7-year forecast 2025-2031 (Spring 2025).

Constellation	state	Launched	Active	Planned	First launch
Starlink	US	4714	3521	4714	2018
Starlink2A	US	3689	3070	6720	2022
Starlink2	US	0	0	30456	-
OneWeb	UK	660	635	716	2019
OneWeb2	UK	0	0	2304	-
Kuiper	US	29	27	3232	2023
StarShield	US	193	126	32	2022
Xingwang	CN	50	10	996	2021
Qianfan	CN	90	28	32	2024
Guangwang	CN	0	0	12992	-
Yinhe	CN	8	7	1000	2020
Hanwha	KR	0	0	2000	-
Lynk	US	10	6	2000	2020
Astra	US	0	0	13620	-
Telesat	CA	0	0	300	-
HVNET	US	0	0	1440	-
SpinLaunch	US	0	0	1190	-
Globalstar3	DE	0	0	3080	-
Honghu-3	CN	0	0	10000	-
Semaphore	FR	0	0	116640	-
E-Space	US	4	0	337323	2022

Table I: Megaconstellations (planned > 1000) as per filing to the International Telecommunication Union (ITU)

EUROCONTROL’s Network Manager (NM)¹ and binned on Uber’s H3 gridding system [4] for fast processing.

¹NM coordinates Air Traffic Flow and Capacity Management (ATFCM) operations on behalf of EUROCONTROL’s 42 Member States and 2 Comprehensive Member States covering almost all European Civil Aviation Conference (ECAC) States.

This work will use H3 cells at resolution 3 which corresponds to hexagons of average area $12\,393 \text{ km}^2$ and average edge length of 68.979 km [5] as depicted in Fig. 2.

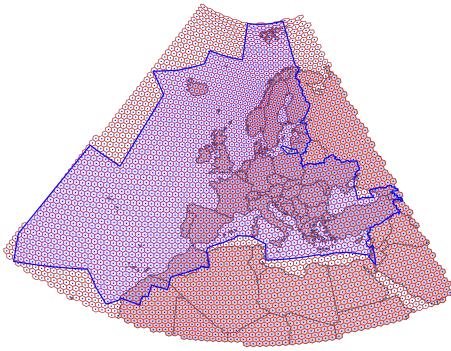


Fig. 2: H3 cells (red) at resolution 3 and their centers (blue) covering the bounding box of 43 EUROCONTROL Member States FIR's (blue shaded polygon).

We characterise densities on an hourly basis for the days of the 2023 and 2024 busiest International Air Transport Association (IATA) summer ISO week.

We expand on the works of [2], [3] and provide a reproducible example for States, Agencies or relevant authorities to build upon.

Next sections will develop the mathematical background for the evaluation of collision and casualty risk of which traffic density is a key component.

Fig. 3 shows hourly flight density for 2024-07-05. Expected outcomes such as cells at zero density for war or no-fly zones (Ukraine, Libya or Syria) or typical traffic flows (North Atlantic, Canaries and East-bound over Türkiye) are clearly highlighted.

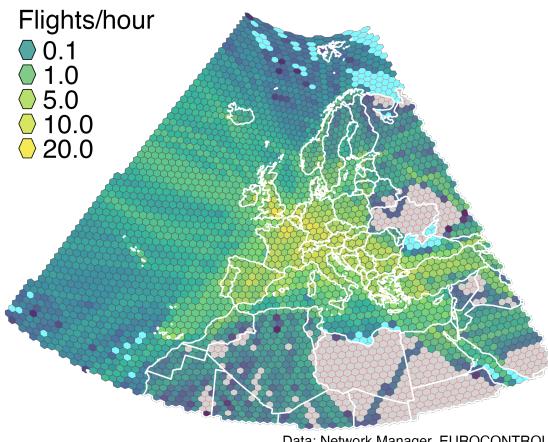


Fig. 3: Flight density in the EUROCONTROL Area on 2024-07-05, the busiest day of the busiest week in 2024 (H3 cells at resolution 3).

A. Impact Probability for Single Flight, Single Debris

The probability, p_k , of a debris (point) object k , impacting an aircraft (point) object over the area, a , is expressed as:

$$p_k = \varepsilon_k \int_a \rho(\vec{x}) \sigma_k(\vec{x}) da$$

where $\rho(\vec{x})$ is the probability density of an aircraft in \vec{x} , $\sigma(\vec{x})$ is the impact probability density of a debris object k in the position \vec{x} and ε_k is the effective exposed area, i.e. the effective risk area for the k^{th} debris object impacting the aircraft (see Section II-B later on).

If we discretize the area of interest a using H3 cells, we have

$$p_k = \varepsilon_k \sum_h \rho(h) \sigma_k(h)$$

So for cell h we have

$$p_k(h) = \varepsilon_k \rho(h) \sigma_k(h)$$

B. Aircraft effective exposed area

We assume the aircraft impact area to be much larger than the debris object area so as to neglect the debris impact area. We can also simplify the geometry of the aircraft and model it as a rectangular solid with dimensions of wingspan, length and height. Now, if the aircraft were stationary, the area exposed to a debris impact would be the top view, while if the debris were stationary it would be the front view. In reality the aircraft is moving (mainly) horizontally and the debris vertically ², which allows to express the effective exposed area, ε_k , as

$$\varepsilon_k = \frac{s_a a_h + s_{d_k} a_v}{s_{d_k}}$$

where s_a is the average aircraft speed, s_{d_k} is the average fall speed of the k -th debris object, a_T area of the aircraft as viewed from the top, a_F area of the aircraft as viewed from the front of the aircraft.

In our calculations we will use (t subscript for aircraft type)

- constant debris fall speed $s_{d_k} = 145 \text{ mph} = S$
- constant aircraft speed, $s_a = C_t$, equal to its cruise speed,
- aircraft area as viewed from the top, $a_T = W_t \times L_t = A_t$, where W_t is the wingspan, and L_t the length for the specific aircraft type t
- aircraft area as viewed from the front, $a_F = W_t \times H_t = F_t$, where W_t is the wingspan, and H_t the height for the specific aircraft type t

The effective exposed area now only depends on the aircraft type t (dimensions and cruise speed) and can be rewritten as:

$$\varepsilon_t = \frac{C_t F_t + S A_t}{S}$$

The values W_t , H_t and L_t have been retrieved from [6]–[8].

The impact probability for cell h and single aircraft of type t becomes:

²Even for a ballistic coefficient of 50 lbs/ft², the flight path angle of a reentering object at 40,000 feet is -86.6 degrees, which corresponds to nearly vertical descent. Since most debris objects have ballistic coefficients equal to or less than 50 lbs/ft², the vertical descent assumption is a very accurate approximation. [2]

$$p_{t,k}(h) = \varepsilon_t \rho_t(h) \sigma_k(h)$$

C. Impact probability density for debris of inclination i

Debris that reenter the Earth's atmosphere via drag-induced decay will fly circular orbits prior to re-entry even if initially on elliptical ones.³

The angular position, θ , of the re-entry point from the ascending node, see Section VI, is uniformly distributed for uncontrolled reentries, $\sigma(\theta) = 1/(2\pi)$. This is due to uncertainties in atmospheric drag and the gravitational effects of the Equatorial bulge. Hence we assume that the impact longitude, λ , is uniformly distributed.

The impact probability density, $\sigma(\varphi, i)$, at latitude φ of a reentering object whose orbit has inclination i (see Fig. 10) is given by [Equation 15 in [2]]:

$$\sigma(\varphi, i) = \frac{1}{2\pi^2 R^2 \sqrt{(\sin^2(i) - \sin^2(\varphi))}} \quad (1)$$

where R is the distance from the center of the Earth of the object potentially being impacted by the debris.

So for example if a building is located at latitude 30 degrees and has an area of 1000 m² and a piece of debris reenters the Earth's atmosphere from an orbit having an inclination of 45 degrees, the impact probability is given by

$$\begin{aligned} P &= \Delta A \times \sigma(\varphi, i) = 1000 \times \sigma\left(\frac{\pi}{6}, \frac{\pi}{4}\right) \\ &= 1000 \times 2.490\,756 \times 10^{-15} = 2.490\,756 \times 10^{-12} \end{aligned}$$

where we used the equatorial value of 6378 km, for the Earth's radius, R , as the distance of the building from the center of the planet.

The impact probability density $\sigma(\varphi, i)$ for an inclination i of 51.7° is plotted in Fig. 4 and takes a characteristic U shape.

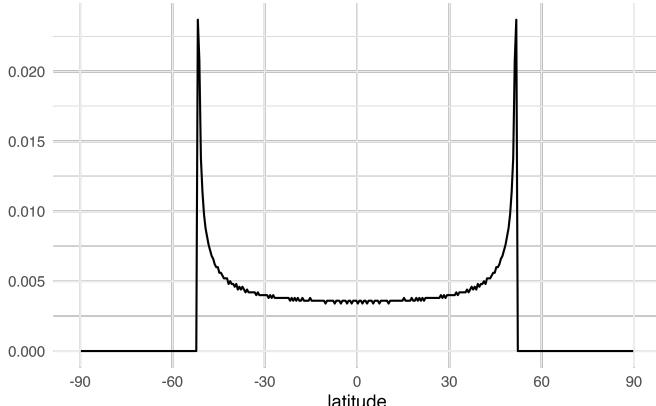


Fig. 4: Impact probability density $\sigma(\varphi, i = 51.7)$ for debris of inclination i and altitude 550 km.

³In fact drag at perigee will lower apogee and similarly drag at apogee will lower perigee. But because drag at perigee is higher due to denser atmosphere, the apogee will decrease faster than perigee and the orbit will then tend to be a circular one.

D. Impact probability density for debris

If we consider historical debris re-entry data, we can numerically derive the debris impact probability as a weighting function by summing up and averaging all single densities:

$$\sigma(\varphi) = \sum_k \sigma(\varphi, i_k)$$

From [9] we extracted 1968 debris re-entries during 25 calendar years from 1st Jan 2000 till 31st Dec 2024. The result of combining all the U-shaped densities can be seen in Fig. 5.

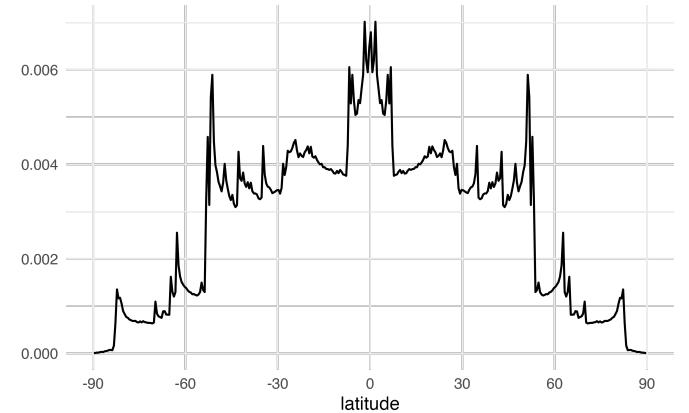


Fig. 5: Weighting function derived from 25 years of re-entries as an empirical approximation of $\sigma(\varphi)$.

Spatially combining $\sigma(\lambda, \varphi)$ for the H3 cells in the NM area we obtain the weightings per cell (per hour) as in Fig. 6.

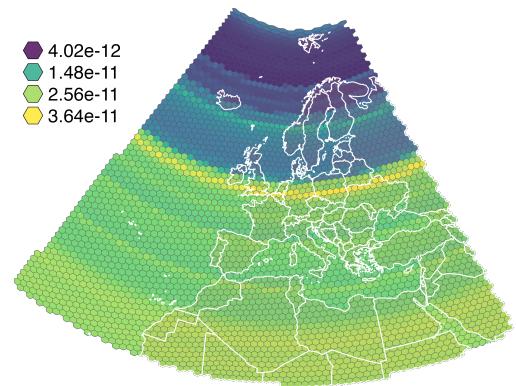


Fig. 6: Weightings for H3 cells in NM area.

E. Hourly impact probability per H3 cell

By combining the hourly aircraft density (per aircraft type) with the relevant weightings per H3 cell, we can numerically compute the hourly impact probability for each hexagonal cell as:

$$E_h = \sum_t W(h) \cdot \rho_t(h) \cdot \varepsilon_t$$

where E_h is the collision expectation in the hexagon h , $W(h)$ is the median value of the weighting function over

the area of hexagon h , t is the International Civil Aviation Organization (ICAO) aircraft type, $\rho_t(h)$ is the traffic density for type t in cell h and ε_T is effective exposed area for aircraft of type t .

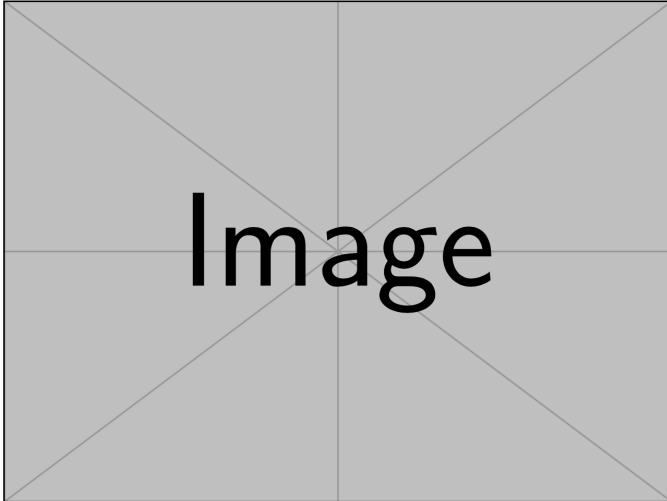


Fig. 7: Collision risk probability.

F. Use Case: KOSMOS 482 Descent Craft re-entry

In few days (at the time of writing this paper) at 6h May 10, 2025 (± 2.8 days), the KOSMOS 482 Descent Craft should reenter the Earth's atmosphere ?. This is supposedly the lander module from a 1972 failed Soviet Venera mission [10] of 480 kg weight and circa 1 m diameter. Being supposed to survive Venus's atmosphere which is much denser and hotter than Earth's atmosphere (surface pressure 93 times that of Earth and temperatures reaching 467 degrees Celsius (872 degrees Fahrenheit)). So it could re-enter Earth intact and not break into smaller fragments some of which could burn up.

With what developed in this paper, we can derive the casualty risk and determine the maximum value using data for the busiest day in the busiest 2024 week.

Once the re-entry track is known more or less accurately, the relevant H3 cells can be

III. DATA AND CODE FOR REPRODUCIBILITY

We have calculated collision and casualty risk probabilities for the two busiest weeks in 2023 and 2024. The relevant dataset represents a data cube as logically depicted in Fig. 9 is available in the companion GitHub repository of the paper at https://github.com/espinelli/flight_density_space_debris. We have also developed a companion R package `aviodebris` to heavylift the various data processing steps to produce the results in the paper; it is available at <https://github.com/espinelli/aviodebris>.

IV. CONCLUSION AND FUTURE WORK

We show how National and/or International authorities could prepare for the more and more likely and frequent occurrence of uncontrolled re-entry of space objects that could

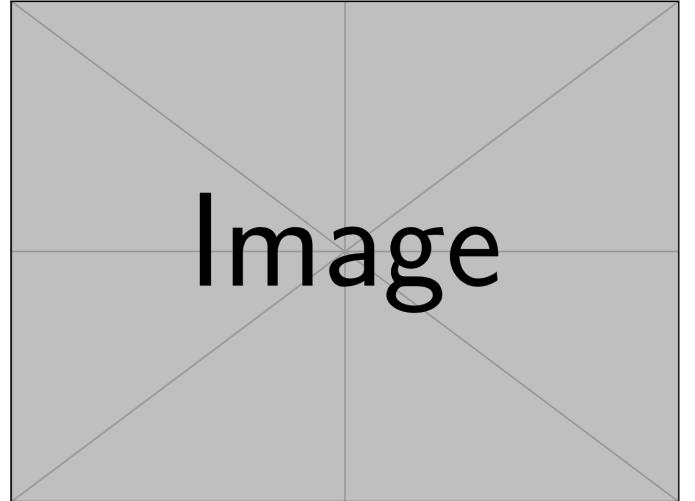


Fig. 8: Casualty for KOSMOS 482 Descent Craft re-entry.

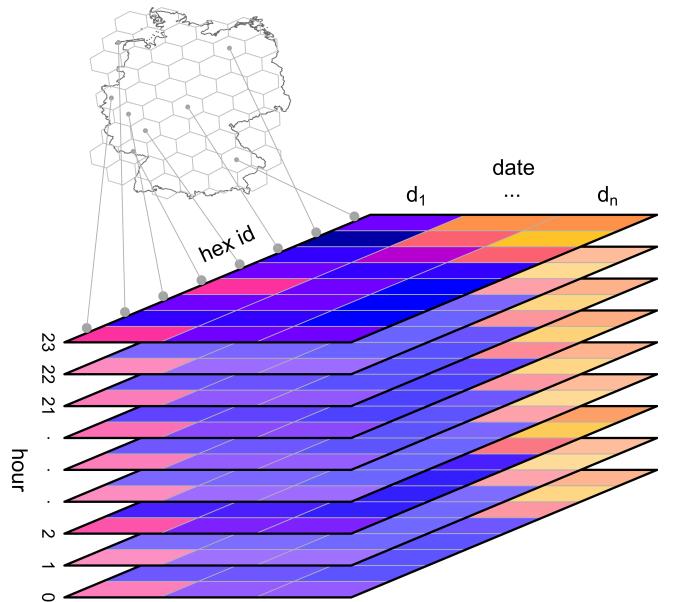


Fig. 9: Data cube of hourly flight densities data over H3 hexes (in Germany) for multiple dates, $d_1 \dots d_n$.

pose a safety concern on civilian aviation. The techniques we implemented on realistic data and sound algorithms can contribute to the bag of tools in the hands of technical and political entities aiming at guaranteeing the utmost safety and minimal economic disruption to civil aviation in Europe.

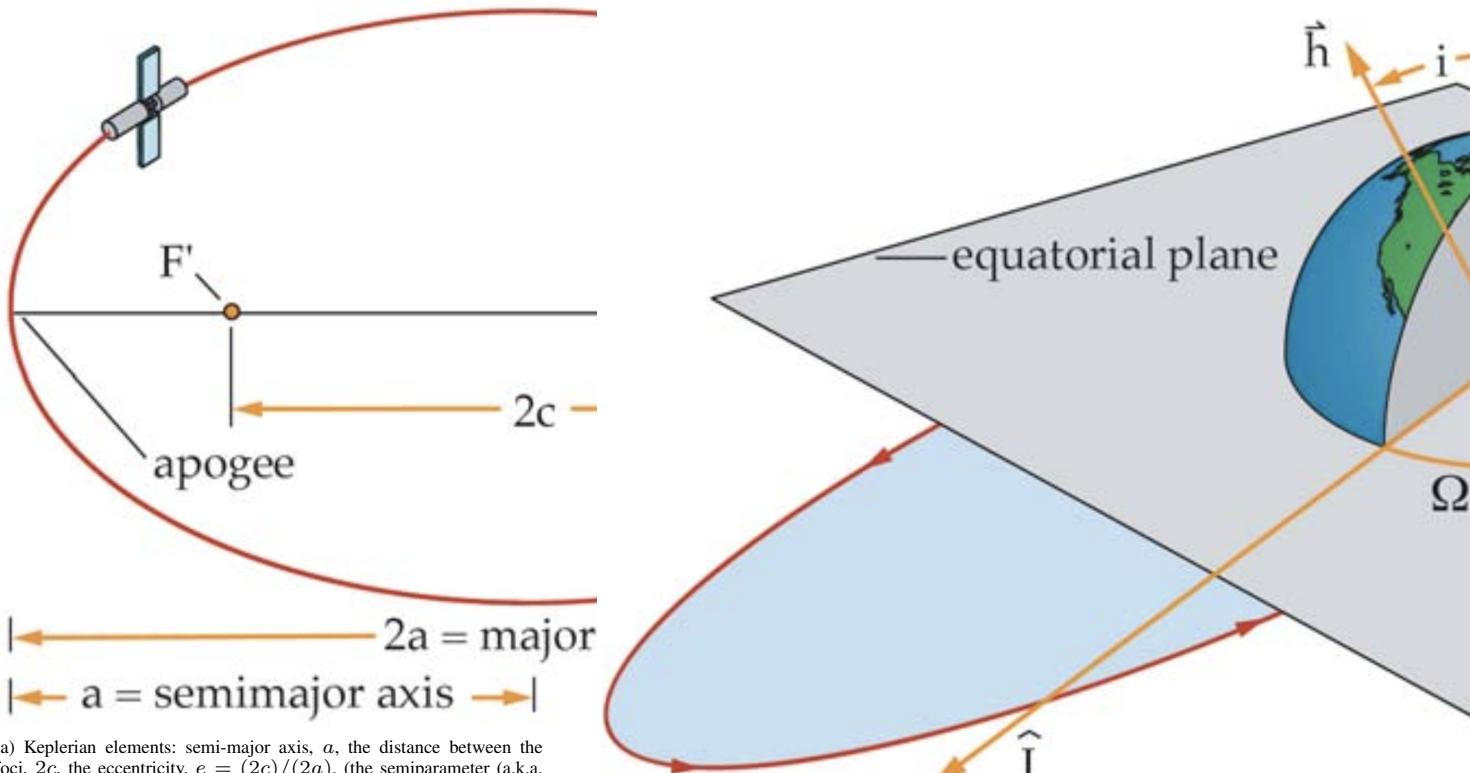
Future work will explore the impact of megastellations and the risk for European airspace.

V. APPENDIX

VI. ORBITAL ELEMENTS

We refer to Fig. 10 to describe the orbital parameters of interest for the current work.

The angular position, θ , of the re-entry point from the ascending node in the orbit plane is $\theta = \omega + \nu$. It is



(a) Keplerian elements: semi-major axis, a , the distance between the foci, $2c$, the eccentricity, $e = (2c)/(2a)$. (the semiparameter (a.k.a. *semilatus rectum*), p , describes the size of the conic section by defining the width at the primary focus, and is defined as $p = b^2/a = a(1 - e^2)$)

Fig. 10: Definition of Keplerian elements. The orbital elements describing the trajectory of orbiting object are illustrated in association with an inertial reference frame $\hat{I}\text{-}\hat{J}\text{-}\hat{K}$. The I -axis, \hat{I} , points toward the vernal equinox and the J -axis, \hat{J} , is perpendicular to the I -axis in the equatorial plane n the sense of Earth's rotation with the K -axis pointing up. The semi-major axis, a , the eccentricity, e , the inclination, i , the right ascension of the ascending node, Ω , and the argument of perapse, ω , constitute, together with the mean anomaly at the initial position, M_0 , a set of six constants of motion that are preserved in the absence of perturbation. True anomaly, ν , specifies the location of an orbiting object within the orbit. It is the angle between perigee and the orbiting object's position vector measured in the direction of the orbiting object's motion. Figures from [11], respectively Figure 5-2 and Figure 5-9.

related to the latitude, φ , via the Cartesian coordinate k , $k = R \sin(\varphi) = R \sin(\theta) \sin(i)$, or

$$\sin(\varphi) = \sin(\theta) \sin(i) \quad (2)$$

Mass of Earth, $M_{\oplus} = 5.9722 \times 10^{24}$ kg.

These are used to derive numerically compute the weighting function, Fig. 4: for debris with inclination i we simulate an orbit of N , i.e. 10001, positions and calculate the corresponding cartesian position and the equivalent longitude and latitude.

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