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EUROPEAN
AVIATION

Digital Avionics Systems Conference

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

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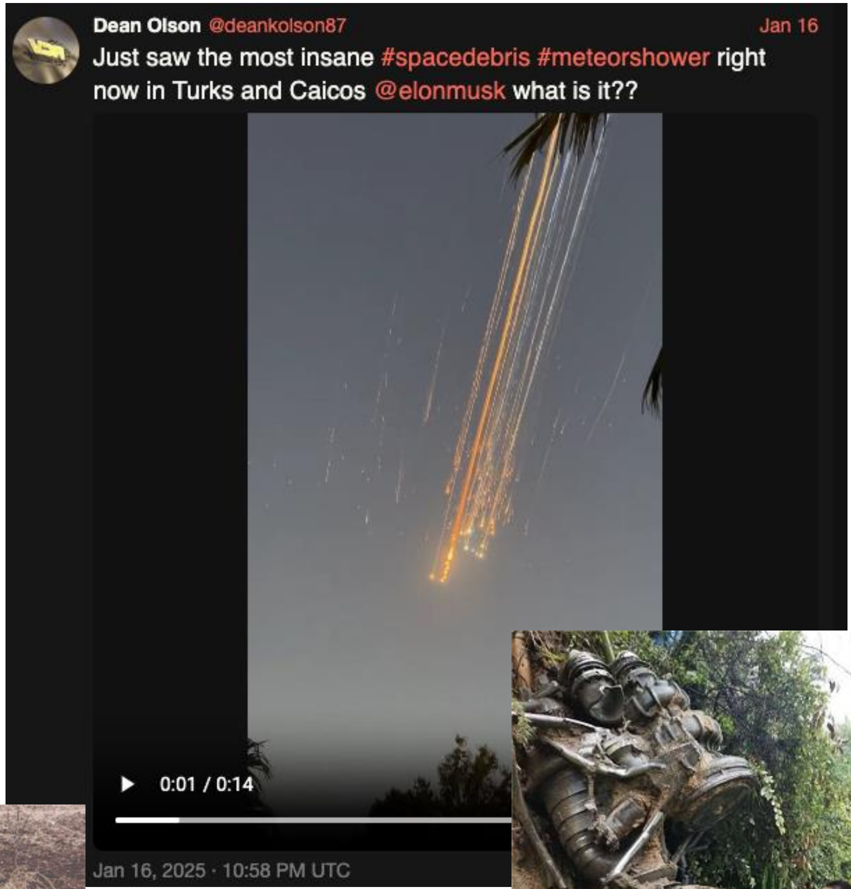
Summary

- What this study is about
- Why performing it
- Who: institutional and geographical scope
- How: method, assumptions and simplifications
- Reproducibility and Thanks
- Future work
- Q&A

What: debris falling from the sky impact on (EU) Aviation

- Space missions result in debris re-entering Earth's atmosphere
- Re-entries can be controlled or **uncontrolled** (launch failure, satellite end of life, …)
- We focus on impact on **airborne** flights, not on people/buildings/… on the ground



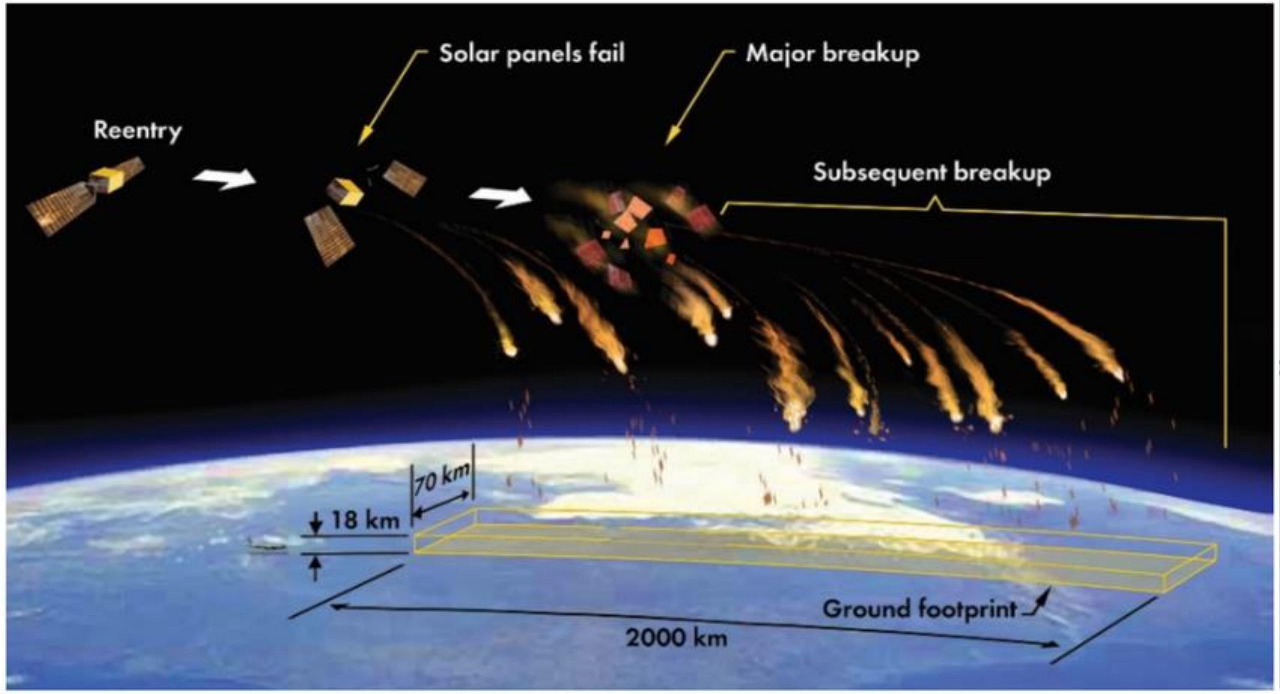
Why dealing with Space Debris in Aviation? 1/2

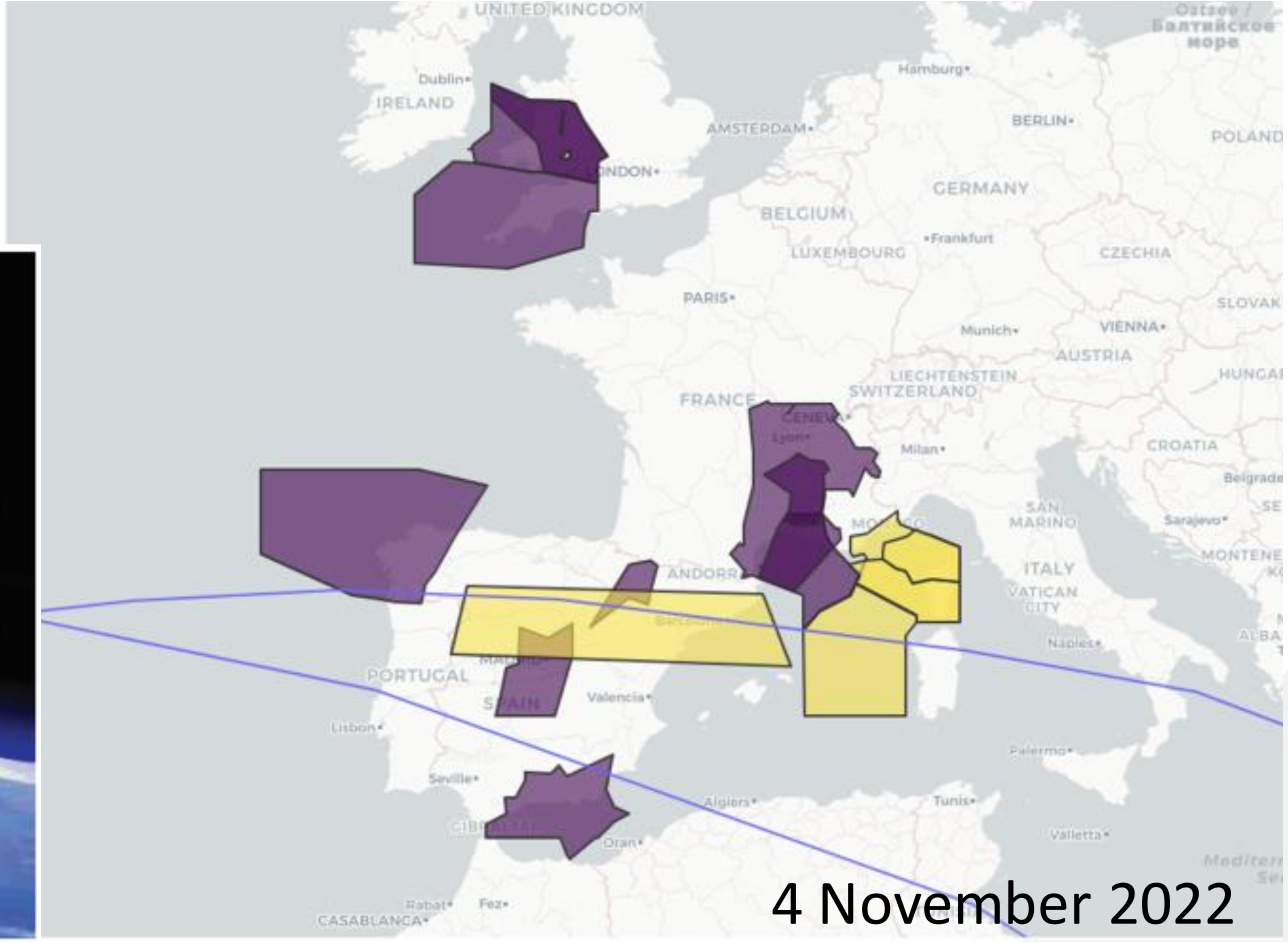
- **Safety**: Damage caused by re-entering debris to a flying aircraft could cause hundreds of casualties
- **Awareness**: growing number of LEO satellites (constellations of **thousands**!) increases the occurrence of uncontrolled re-entries.
  Let's quantify the risk!
- **Resilience**: be ready to **consistently** put measures in place on short notice & **rationally** (rather than emotionally)

Why dealing with Space Debris in Aviation? 2/2

- lack of harmonization of responses among States impacted by Long March 5B reentry on 4th Nov 2022

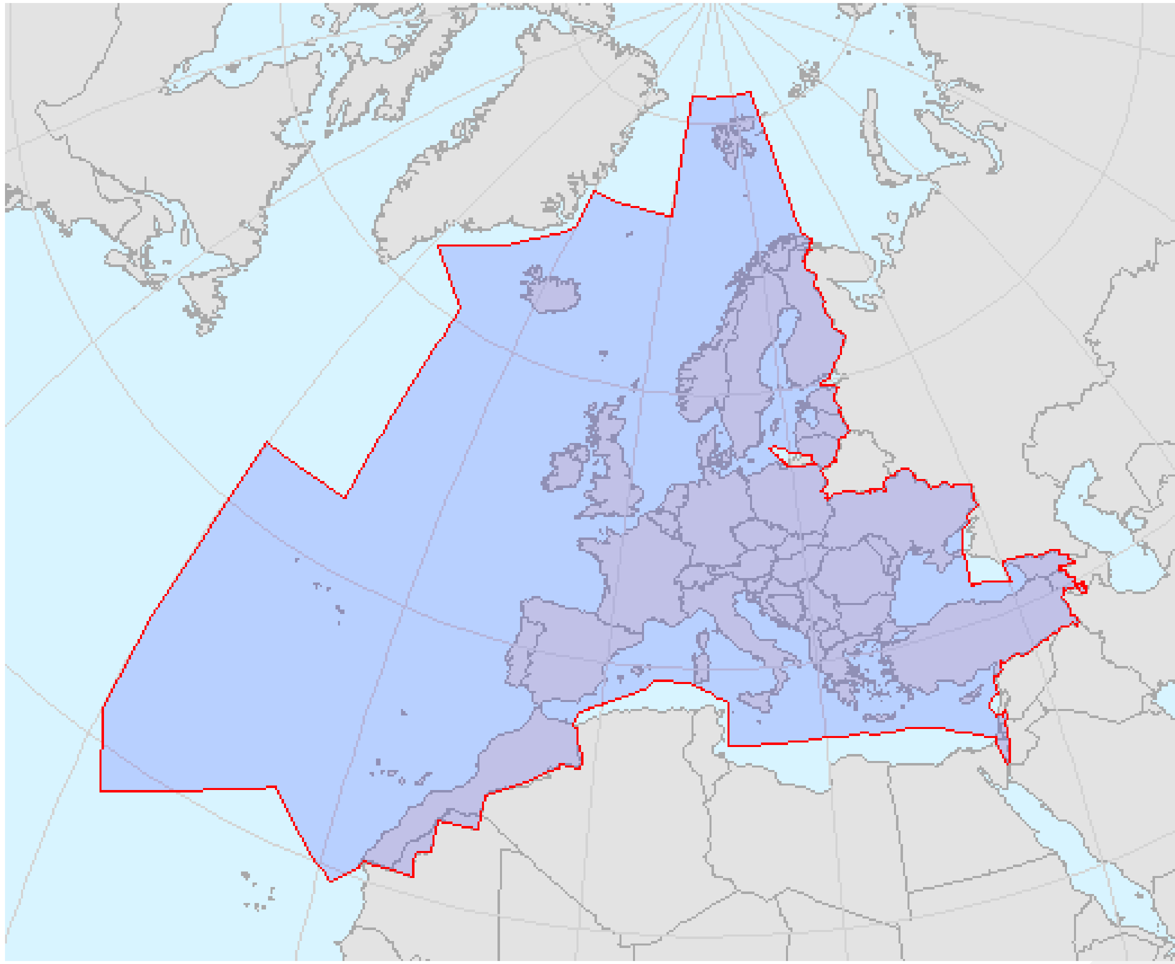
Long March 5B reentry tracks (blue line) over EU
zero rate (closure) NOTAMs in yellow
non-zero rate (advisory) NOTAMs in purple. [3]





Who: EUROCONTROL

- 43 Member States' FIRs (NM Area, blue area)
- Analysis for bounding box containing all FIRs
- Use **full** flight trajectories as IFR flights filed/flown by airspace users crossing NM Area;
  past works used as proxies for trajectories
  - Population density
  - ADS-B position reports (including on ground and no flight type distinction, IFR/VFR, GA, …)



Area, a, of the study

Method: Step 1, general formulation

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probability p_k of a debris (point) object k impacting an aircraft (point) object over the area a

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

probability density of an aircraft in the position $\vec{x}$

impact probability density of a (point) debris object k in the position $\vec{x}$

area a of interest

aircraft **effective exposed area** to debris k

$$\varepsilon_k = \frac{s_a a_F + s_{d_k} a_T}{s_{d_k}}$$

aircraft area viewed from **F**ront

aircraft area viewed from **T**op

average speed of aircraft a

average fall speed of debris k

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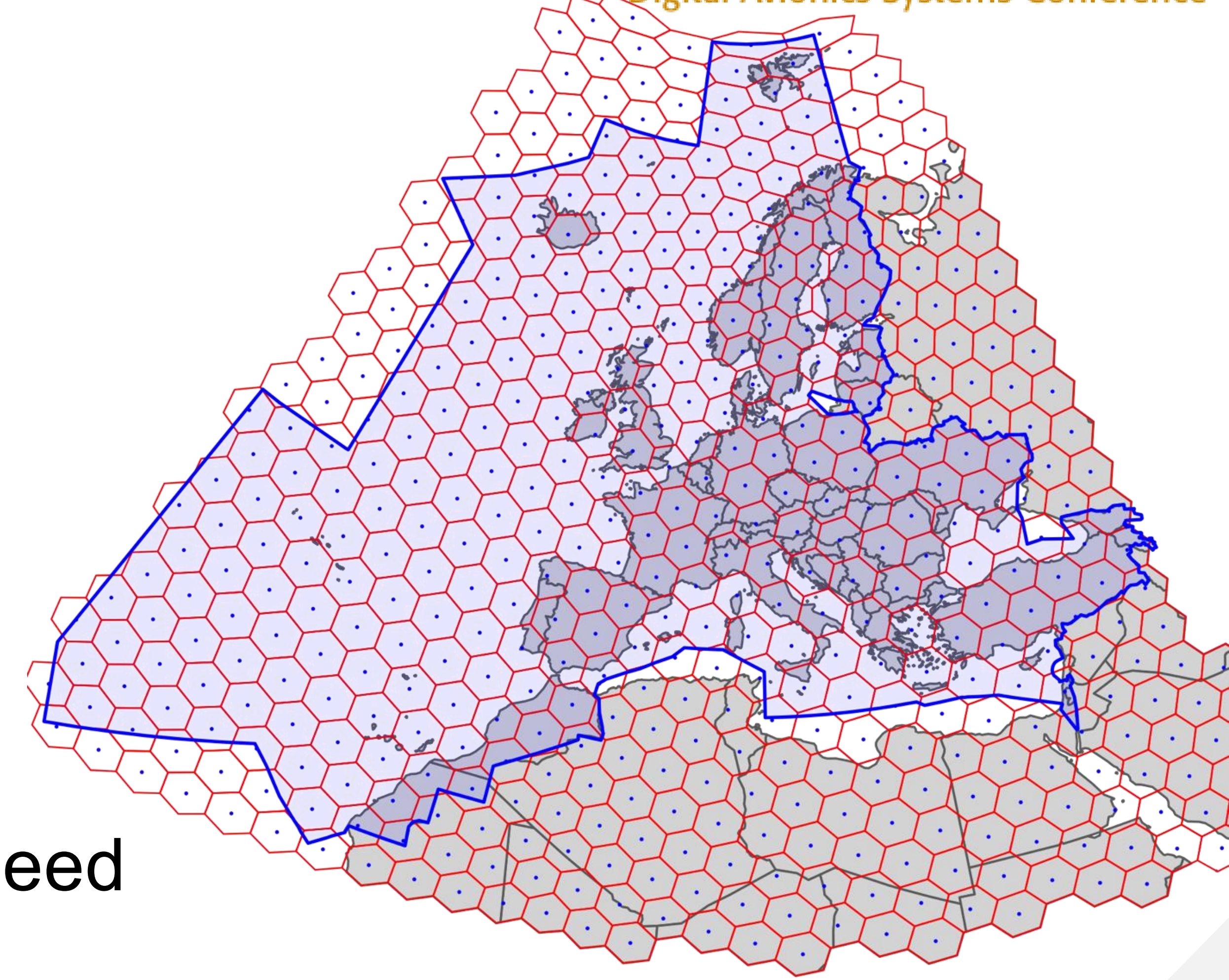
Step 2.1, discretize & assumptions

- Discretize using Uber's H3 cells **<u>resolution 3</u>** hex:
  - edge ~69 km / 37.3 NM
  - area ~14000 km^2 / 5400 mi^2
- Trajectories sampled every 30s

<u>Assumptions</u>

- 1 debris, 1 piece
- Constant aircraft speed = cruise speed for relevant aircraft type
- Point debris **all** falling vertically at 145 mph [2]



(Bounding box) Area, a, of the study (shown hex cell at resolution 2 [coarse] rather than 3 [finer] as in the paper)

Step 2.2, discretize + assumptions

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debris k impact probability for cell h

probability density of an aircraft being in cell h

$$p_k = \sum_{\text{h}} p_k(h) = \varepsilon_k \sum_{\text{h}} \rho(h)\sigma_k(h)$$

impact probability density of debris k in cell h

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Step 2.3, discretize + assumptions

aircraft **effective exposed area**

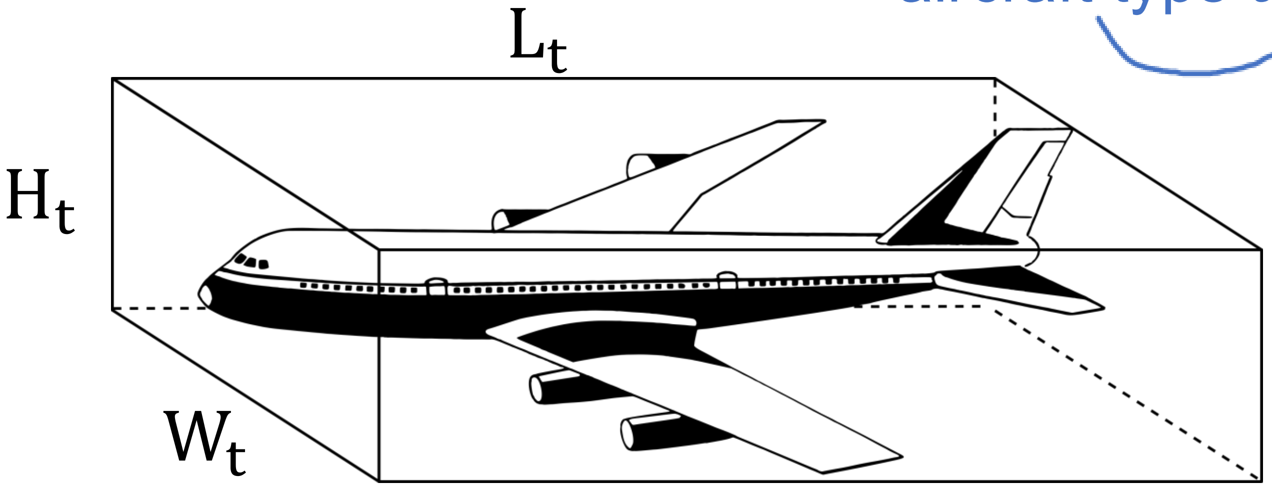
area from
Front / Top

$$\varepsilon_k = \frac{s_a a_F + s_{d_k} a_T}{s_{d_k}} \longrightarrow \varepsilon_t = \frac{C_t F_t + S\, T_t}{S}$$

from debris k to
aircraft type t

cruise speed for
aircraft type t

constant fall
speed for
any debris



$$F_t = W_t \cdot H_t$$

$$T_t = W_t \cdot L_t$$

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Method: step 2

"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

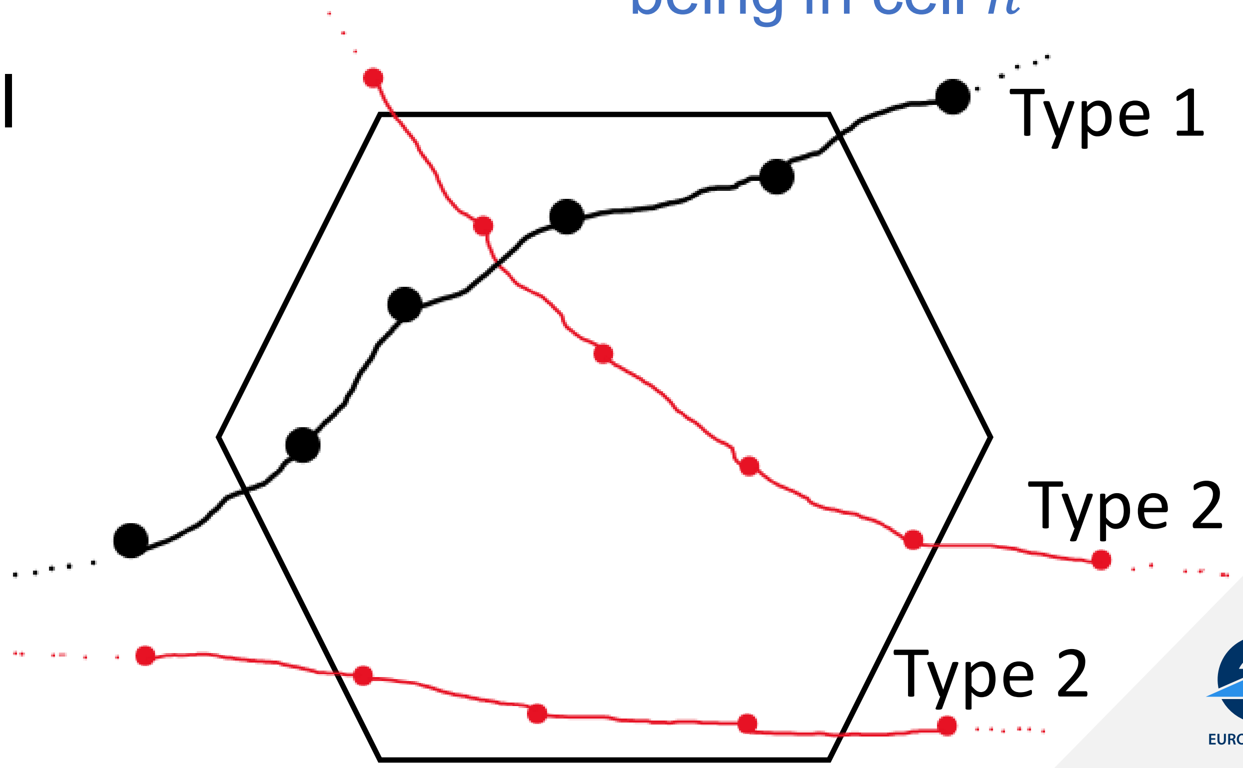
Step 3, aircraft probability density

$$p_k = \sum_{\mathrm{h}} p_k(h) = \varepsilon_k \sum_{\mathrm{h}} \rho(h)\sigma_k(h) = \sum_{\mathrm{h}} \sigma_k(h) \sum_{\mathrm{t}} \varepsilon_{\mathrm{t}}\, \rho_t(h)$$

probability of
aircraft of type t
being in cell h

$\rho_t(h)$ is JUST the sum of the number of points per type t in cell h (per interval of time, i.e. hour)

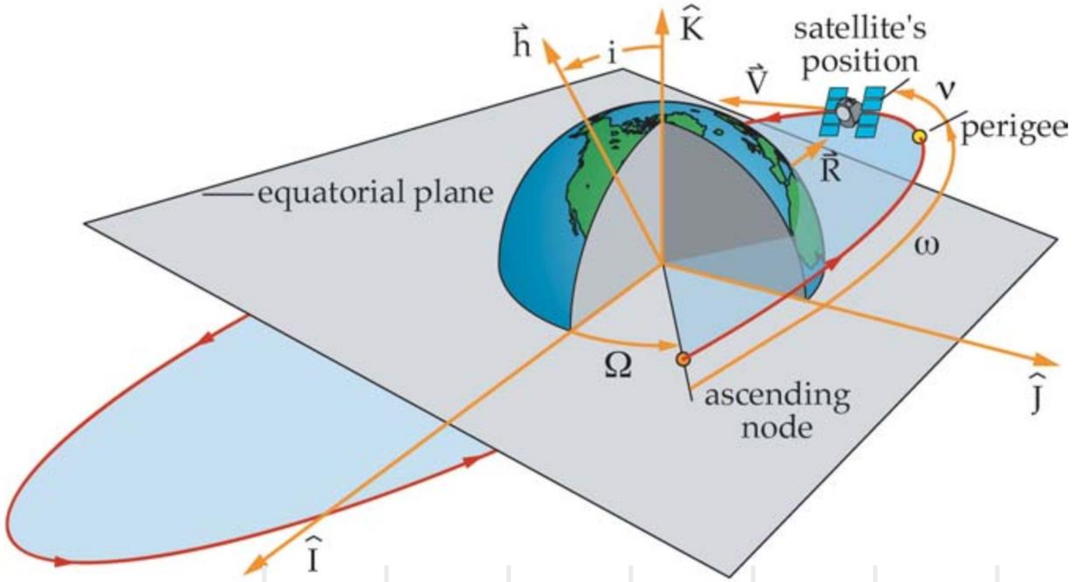
Each trajectory point is 30s apart

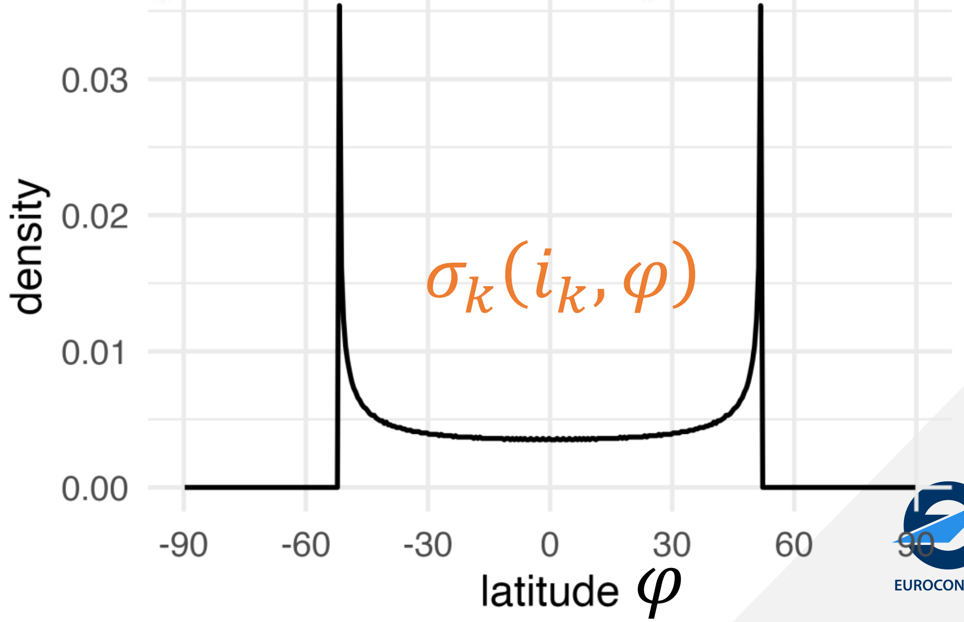


Step 4.1, impact probability density

- A debris k in **uncontrolled** re-entry tends to fly **circular orbit** of inclination i
- uncertainties in atmospheric drag and the gravitational effects of the Equatorial bulge → $\sigma(\theta) = \frac{1}{2\pi}$ **complete uncertainty on longitude θ**
- Density distribution for **latitude φ** only depends on **orbit inclination i**

$$\sigma_k(h) = \sigma_k(h, i, \theta, \varphi)$$
$$= \sigma_k(h, \theta) \cdot \sigma_k(h, i, \varphi)$$

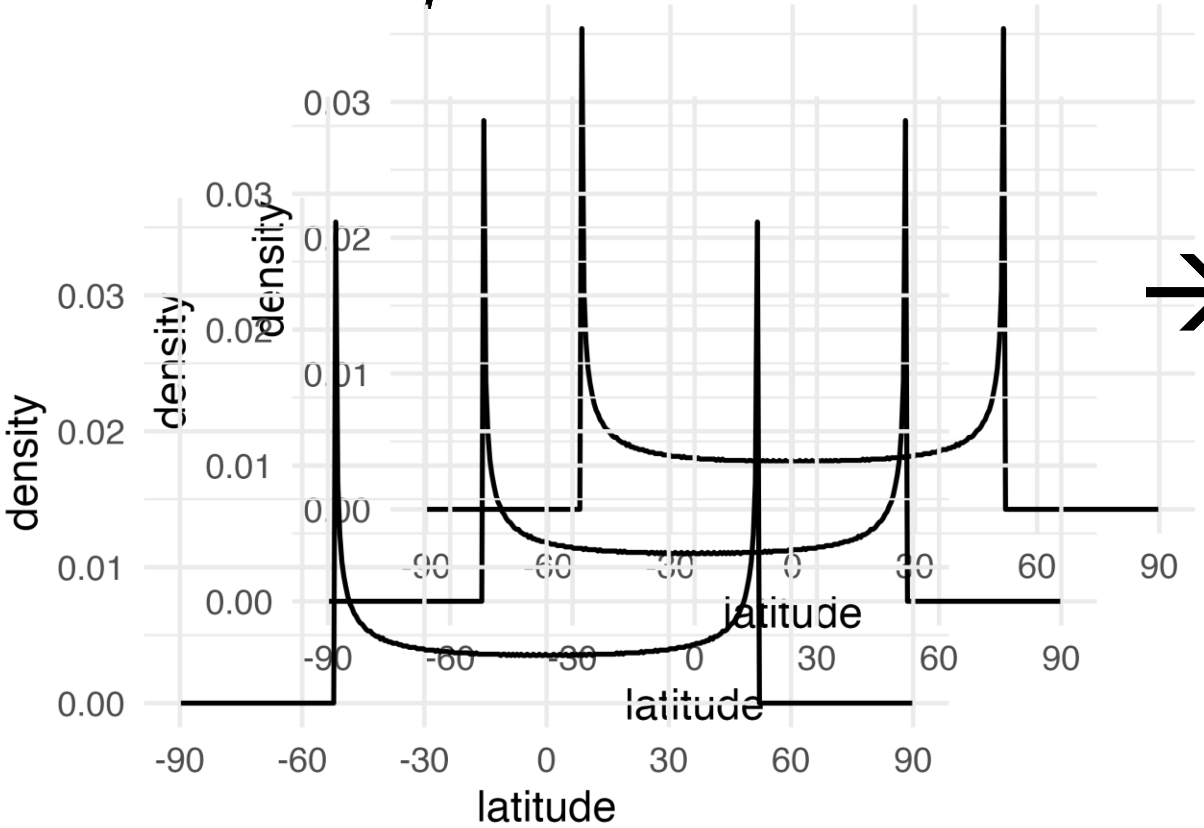




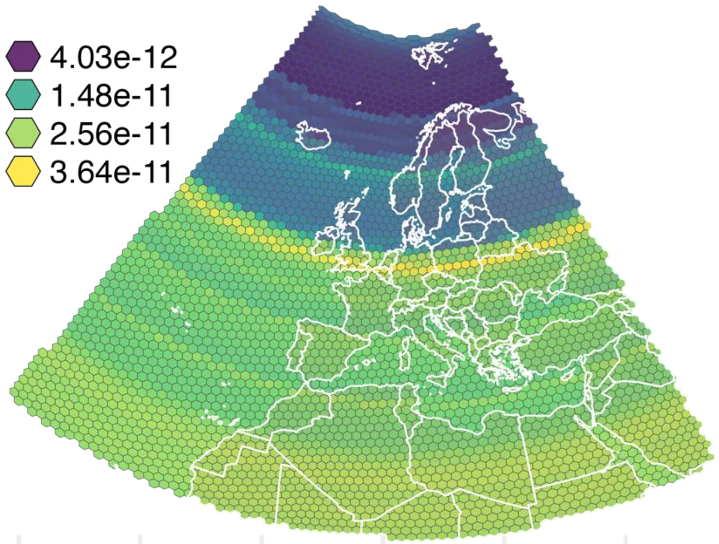
Step 4.2, impact probability density

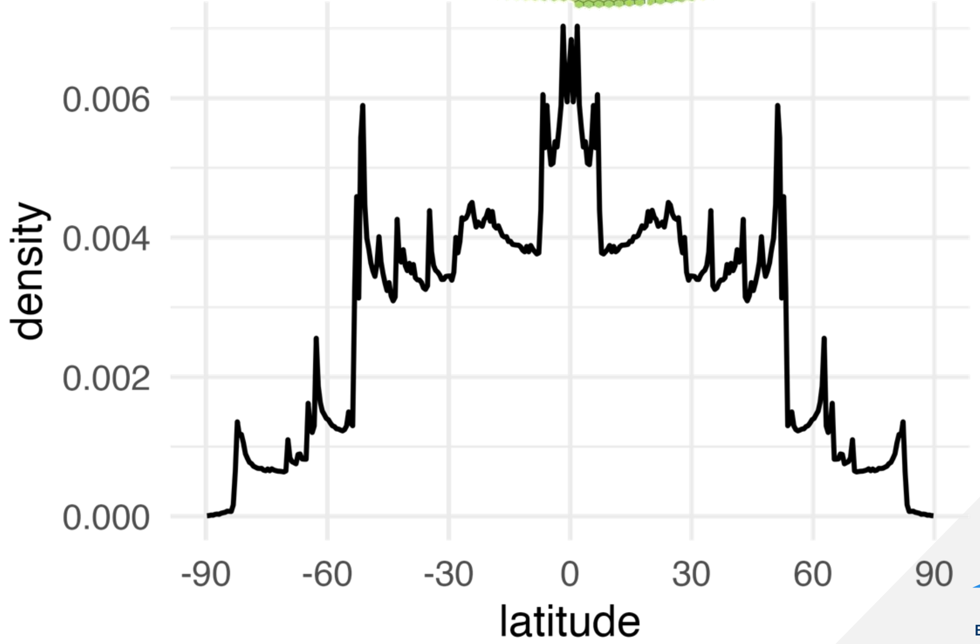
1968 debris re-entries

- We learn from the past 25 years: combine all past debris densities by latitude φ

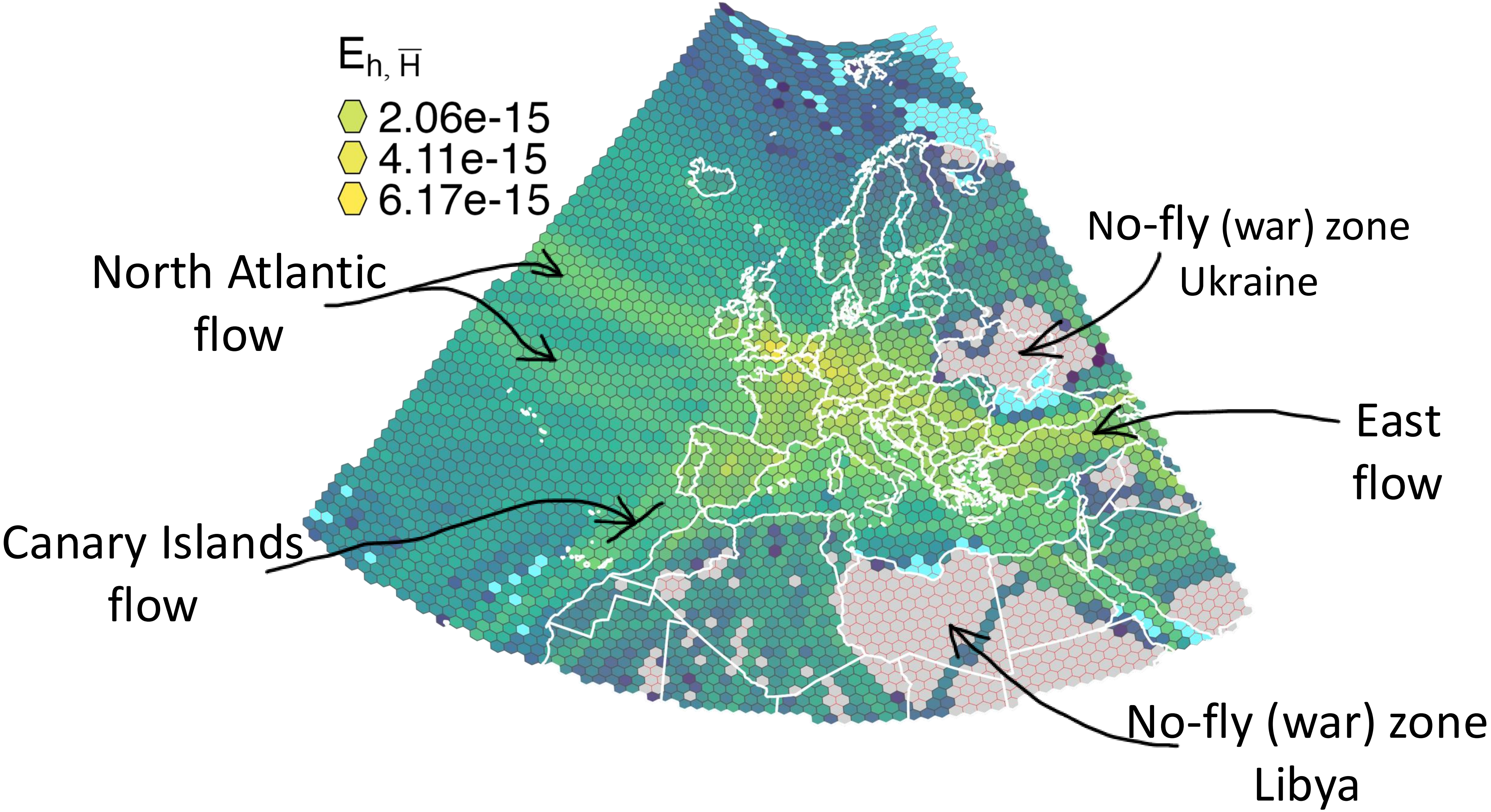


→ Σ →





All combined, 2024-07-05 hourly



Use Case: Kosmos 482

- Inclination $i = \mathbf{51.95°}$
- Use trajectories of busiest day in 2024
- Highest probability collision risk of $2.63 \cdot 10^{-10}$ at a cell overlapping with London Heathrow
- Ten times less probable than being struck by lightining

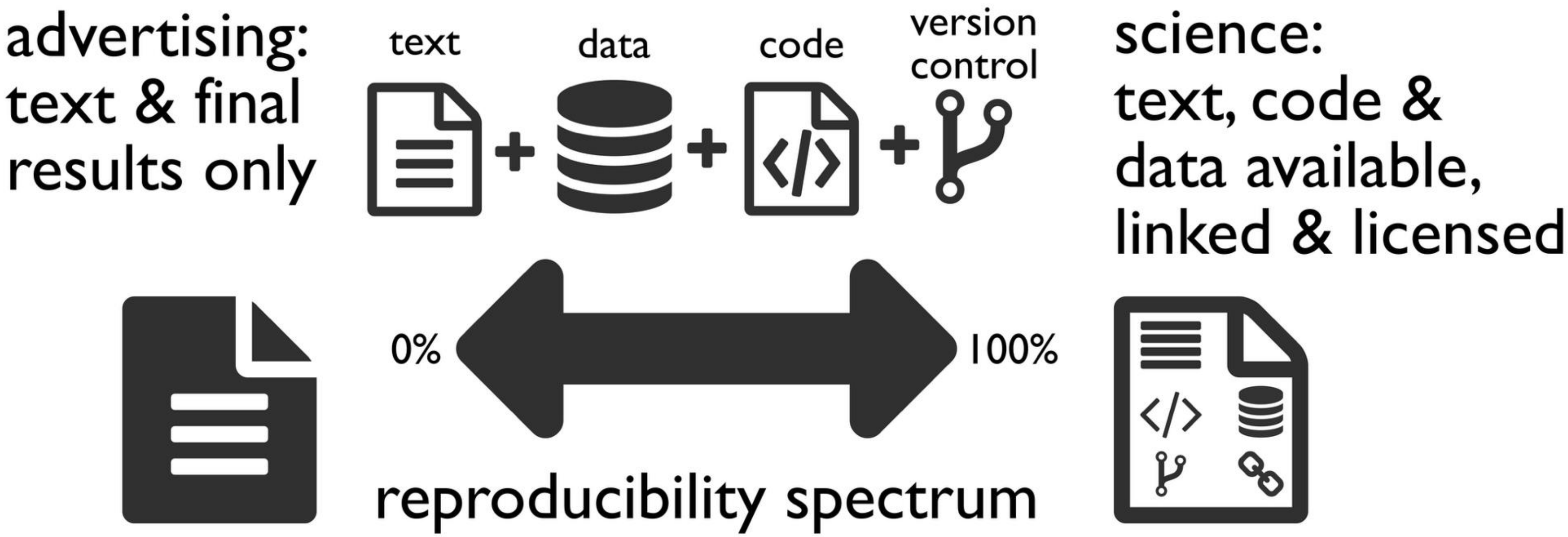
- From failed 1972 USSR Venera mission
- 480 kg, 1m diameter

Reproducible research, 1/2

- Paper source (in Quarto format) and Figures reproduction (in R) (1)
- `aviodebris` R package for processing (2)
- (partial) trajectory data (1)

(1) https://github.com/euctrl-pru/flight_density_space_debris

(2) https://github.com/euctrl-pru/aviodebris



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Reproducible research, 2/2

- We are particularly indebted to

- E. Wright, A. Boley, and M. Byers for their work and availability of Python code that made our learning and understanding of their research much easier
- Jonathan C. McDowell for his tireless effort in keeping alive and up to date the “*General Catalog of Artificial Space Objects*”

Future work

- Consider planned growing traffic and mega-constellations (with a certain rate of uncontrolled re-entries)
- Compute **casualties probabilities** using PAX per aircraft type
- Develop procedure for measures (airspace closure, re-routing) to deal with future uncontrolled re-entries or launch failures
- (Consider people densities at **airports** ?)

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Thank you!

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