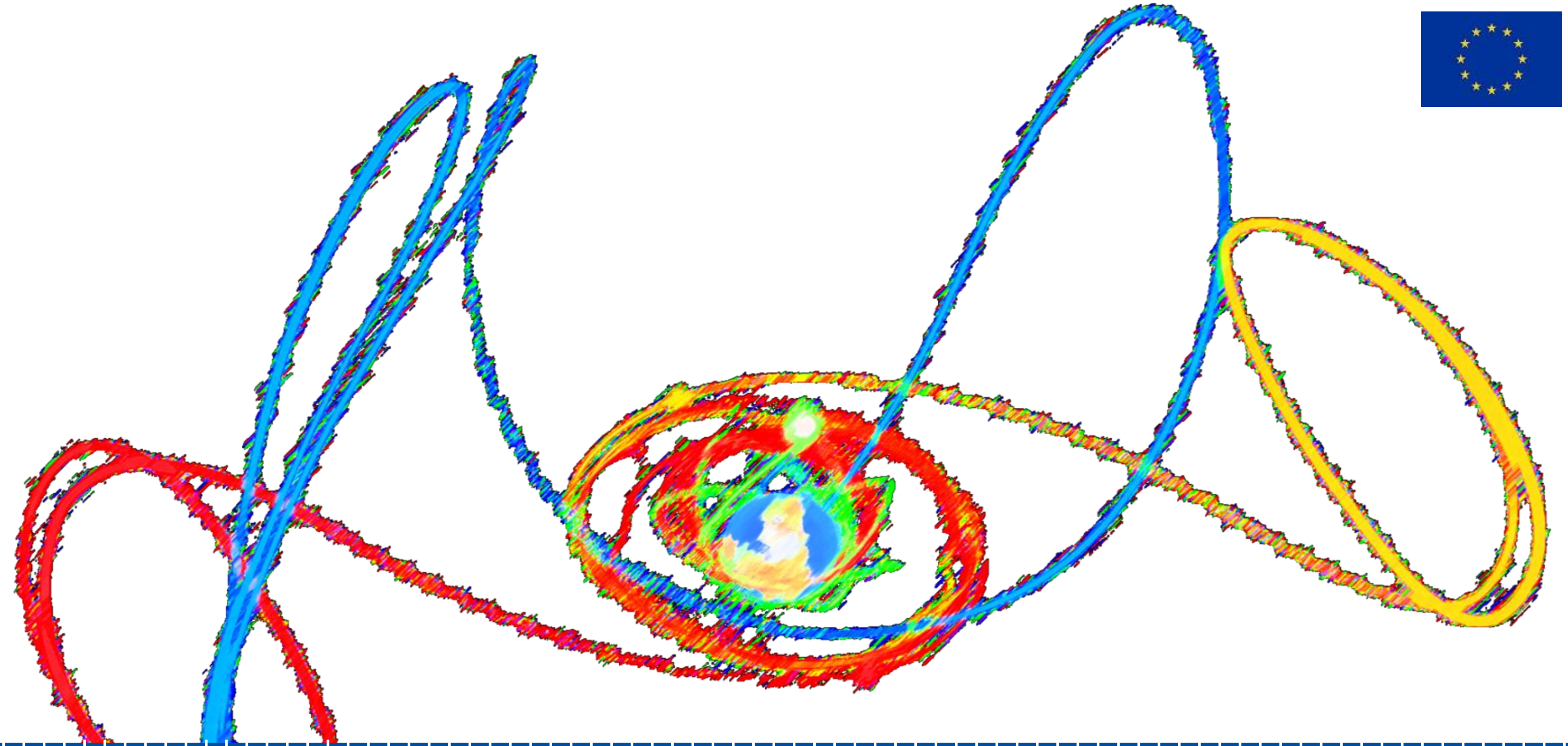


Advancement of a density-based debris fragment model and application to on-orbit break-up localisation

Stefan Frey[1], Camilla Colombo[1], Stijn Lemmens[2]

[1] *Politecnico di Milano*, [2] *European Space Agency*

36th IADC Plenary Meeting, Tsukuba, Japan, 5-8 June 2018

Introduction

Why a density-based debris model?

- Statistical collision risk estimation from objects down to very small sizes
- Inherently statistical (no need of Monte Carlo runs)
- Insight and fast propagation of cloud evolution in any orbital regime subject to major perturbations
- Application to criticality index computation
- Tracing newly observed fragments back to origin, possibly years away

Based on past work by Letizia, Colombo and Lewis @ Uni of Southampton

- Generalise the method (in LEO some parameter are randomly distributed) to any orbital region
- Remove some simplifying assumptions
- Broader application to space debris population propagation

Force model

Orbital contraction

- The integrals can be approximated quickly numerically or analytically
  - E.g. *Gauss-Legendre* quadrature
    - + Flexible: can work with any drag model
    - + Valid for any eccentricity, i.e. series expansion avoided
    - – Multiple density evaluations (usually $N = 33$)
  - E.g. *King-Hele* (KH) method
    - – Requires atmosphere to decay exponentially (next slide)
    - – Series expansion in eccentricity (solved for low and high eccentricities by KH)
    - + Only one density evaluation at perigee
    - + Analytical estimation of the Jacobian available

➢ *Liu, J. J. F., Alford, R. L., An Introduction to Gauss-Legendre Quadrature, Northrop Services, Inc., 1973.*
➢ *King-Hele, D., Theory of Satellite Orbits in an Atmosphere, London Butterworths, 1964*

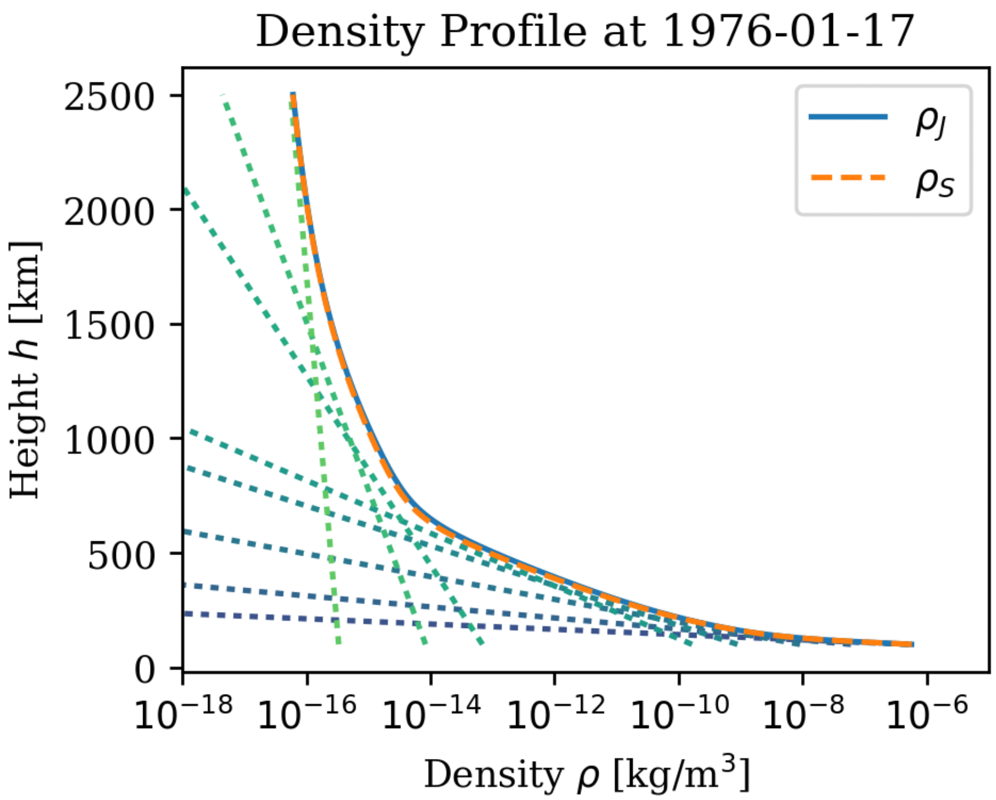
Force model

Atmosphere density model

- The King-Hele method assumes strictly exponential decaying density but in turn requires only one density evaluation at perigee
- Problem: Density decays slower with increasing altitude
- Solution: Smooth exponential atmosphere model

$$\rho(h,T) = \sum_p \rho_{0,p}(T)\exp - \frac{h}{H_p(T)}$$

- Advantages
  - Fast: only p < 10 exponential evaluations required
  - Smooth: no problem for the integrator
  - Exact: each part is strictly decaying
  - Versatile: can be fit to any reference model
- Example: Fit to Jacchia-77 taking into account solar flux



➢ *Jacchia, L. G., Thermospheric temperature, density, and composition: new models. SAO Special Report, 1977.*

DENSITY PROPAGATION

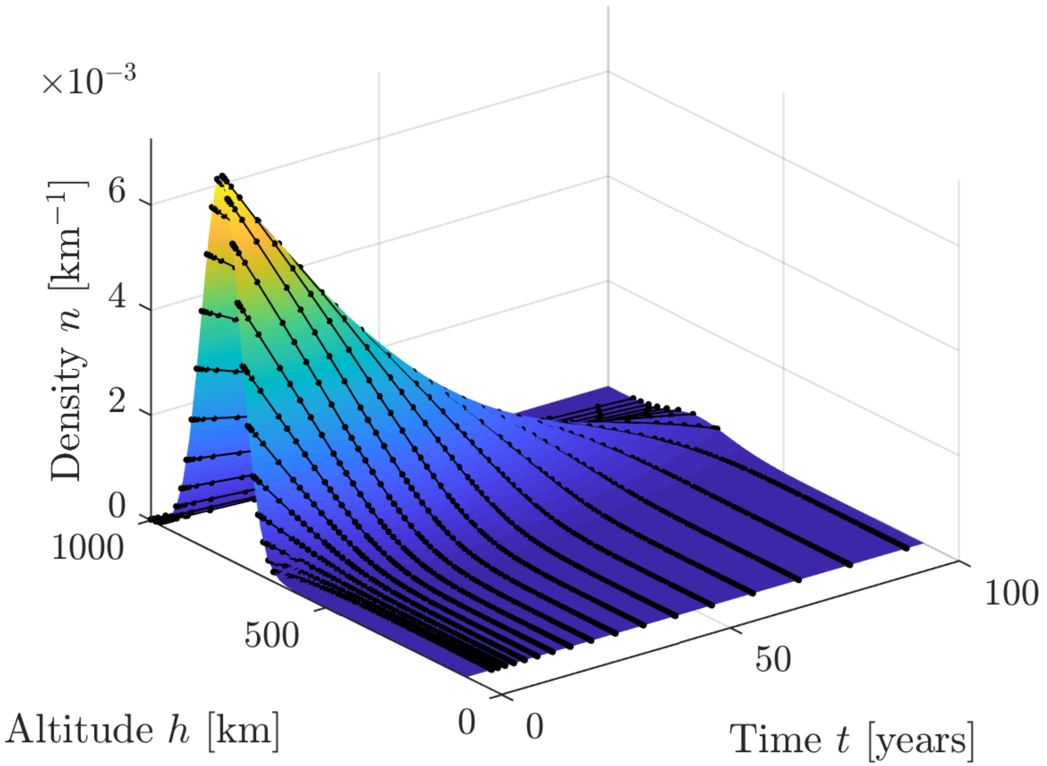
Density Propagation

Formulation

- Fragments/debris modelled as a continuum
- Based on general continuity equation

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\boldsymbol{F}) = g$$

  - n density
  - t time
  - $\boldsymbol{F}$ dynamics
  - g sources and sinks
- Can be turned into a PDE using method of the characteristics
- Requires Jacobian, which is obtainable using analytical formulated dynamics



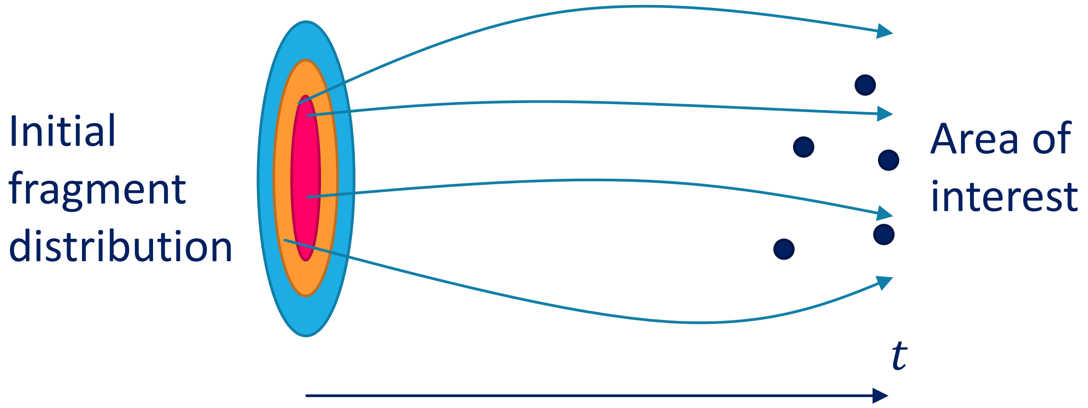
Density Propagation

Propagation method

Population-driven forward propagation

Propagate initial density of a cloud/many clouds/the whole population forward and interpolate where needed.

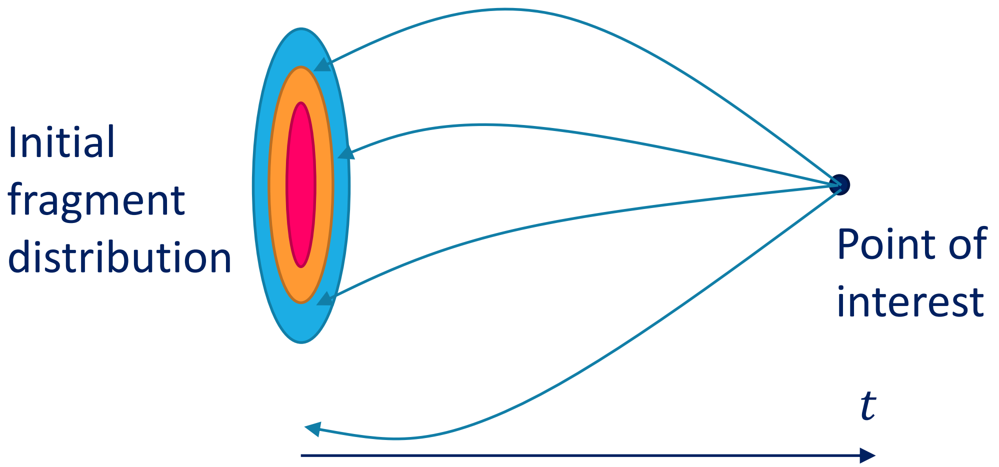
Ideal if density needs to be known at many points



Target-driven backward propagation

Given a target location and time, propagate characteristics backward to initial density.

Ideal if high accuracy in density is required

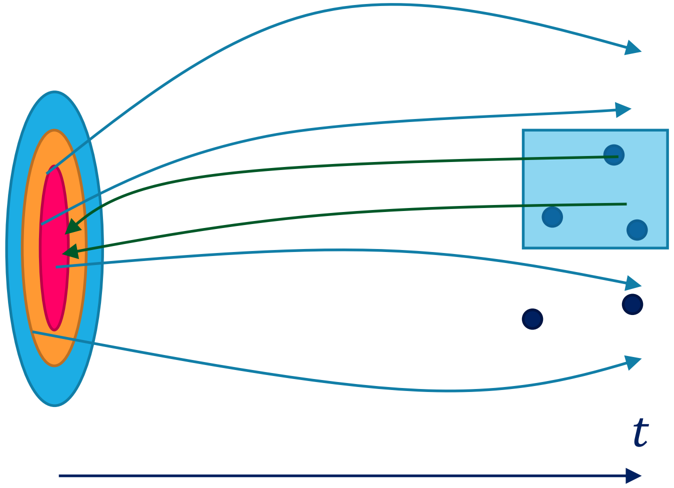


Density Propagation

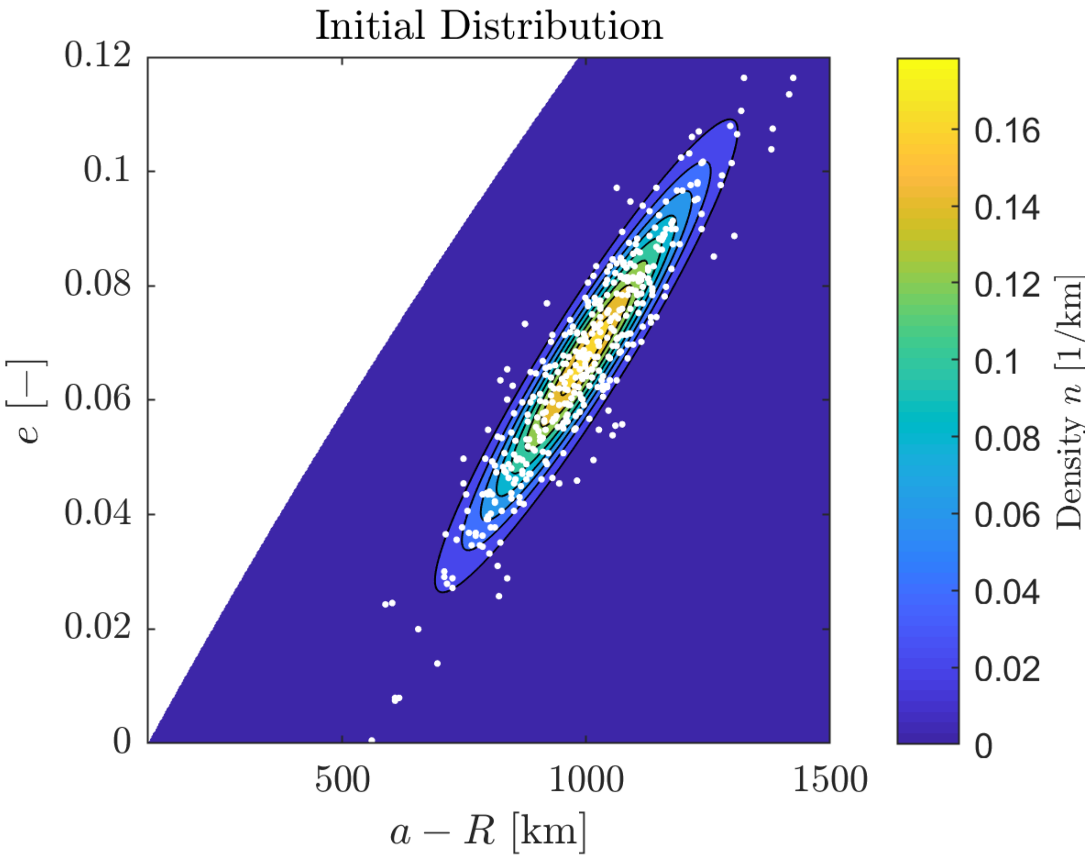
Initial points selection

- Curse of dimensionality workaround:
  - Sample initial distribution, e.g. few points where density low
  - Use combination of population-driven forward to identify the admissible region to be used for target-driven backward propagation

Initial fragment distribution



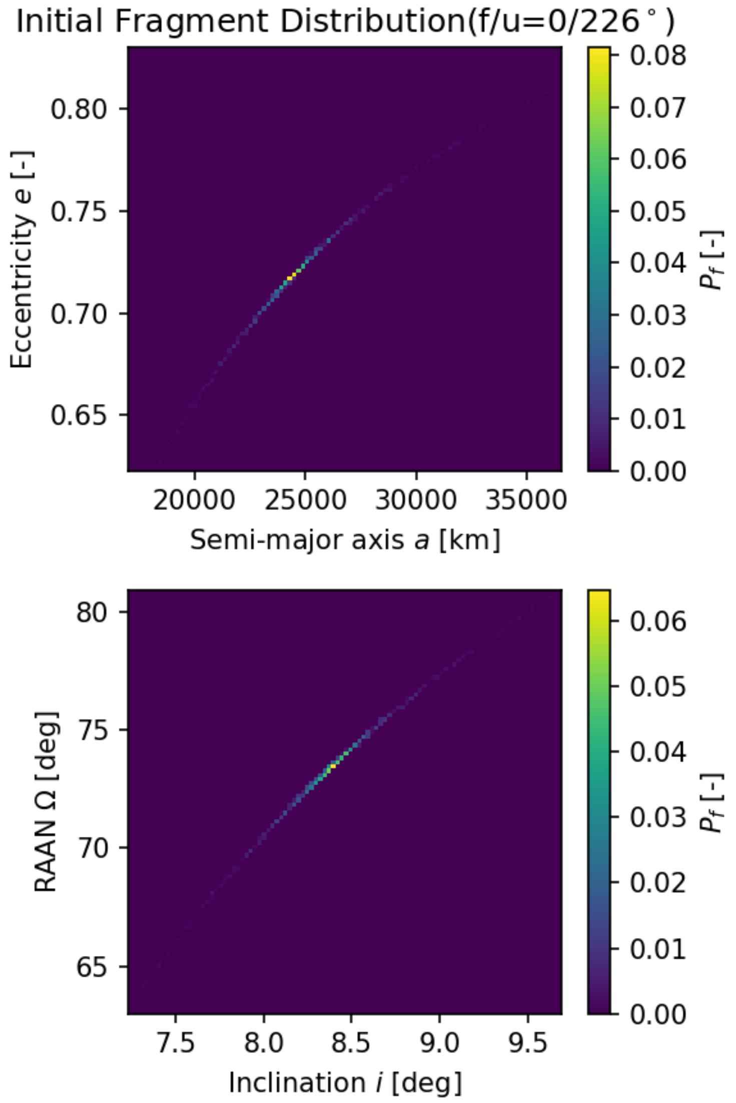
Area of low information



Density Propagation

Building of initial condition

- Initial condition for fragmentations from break-up models (e.g. NASA's breakup model)
- Initial condition for background population from observations or space debris environmental tools (e.g. ESA's MASTER)
- Dimensions
  - up to 5 states $(a, e, i, \Omega, \omega)$
  - physical properties $(\frac{A}{m}, c_d, c_r)$



Fragment distribution for break-up in GTO

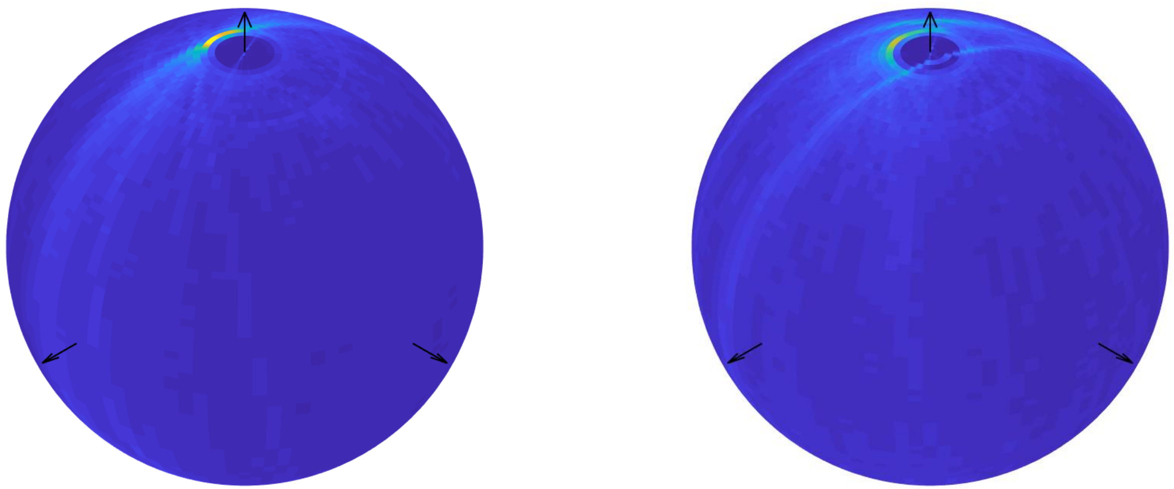
- N. L. Johnson, P. H. Krisko, J.-C. Liou, and P. D. Anz-Maedor. NASA's new breakup model of EVOLVE 4.0. Advances in Space Research, 28(9):1377-1384, 2001.
- S. Flegel, J. Gelhaus, M. Möckel, C. Wiedemann, and D. Kempf. Maintenance of the ESA MASTER model. Final Report of ESA contract 21705/D/HK, 2010.

Density Propagation

From Keplerian to spatial density

- From propagation, the density is given in Keplerian elements
- For collision risk calculation, a spatial density is required
- Not a point-to-point transformation, hence not straightforward
- If anomaly, node and perigee are randomised, the density can be found as a function of radius and latitude
- Currently ongoing: transforming without assumptions

Spatial density from individual fragments in LEO



1 January 2008
4607 objects

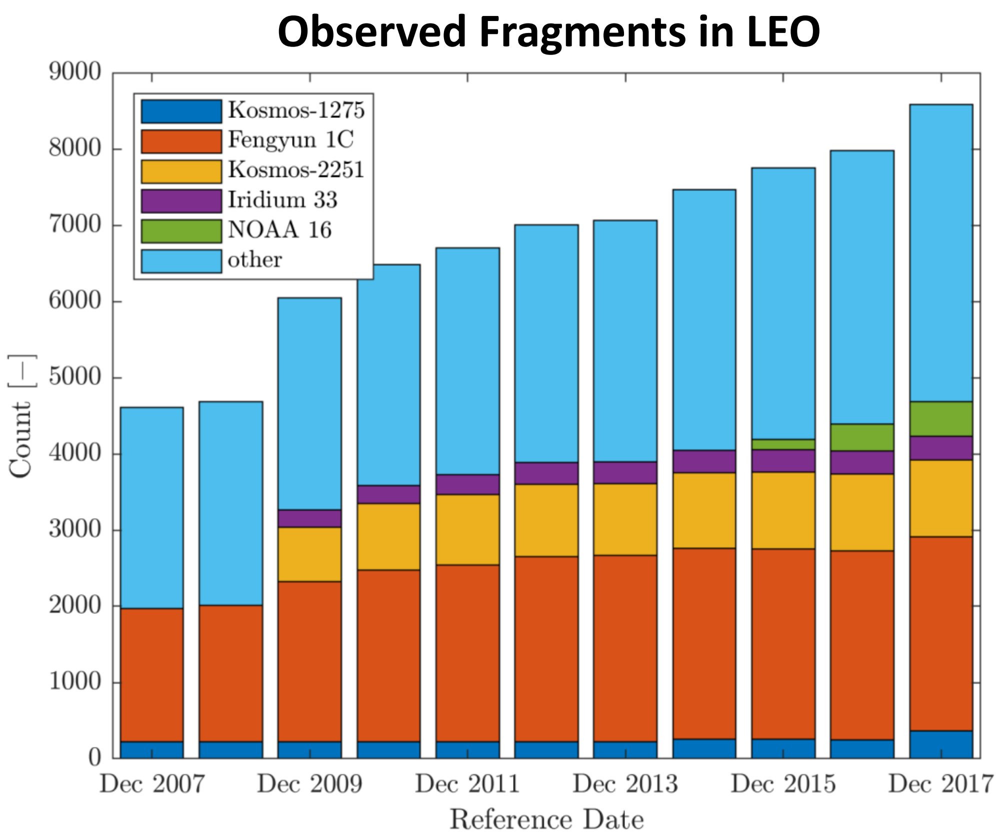
1 January 2010
6047 objects

BREAK-UP LOCALISATION

Break-up localisation

Need

- Ever increasing observational capabilities will add small fragments of unknown origin to the catalogue (e.g. recent major fragmentation of Transtage 17 (1969-013B) in GEO)
- Already now, almost 2500 unidentified objects are tracked, mostly non-LEO
- Due to lack of observations, origin can only be assigned probabilistically
- Application for density propagation, if number of objects with unknown origin is large
- However, at this point, number of fragments small enough for individual propagation



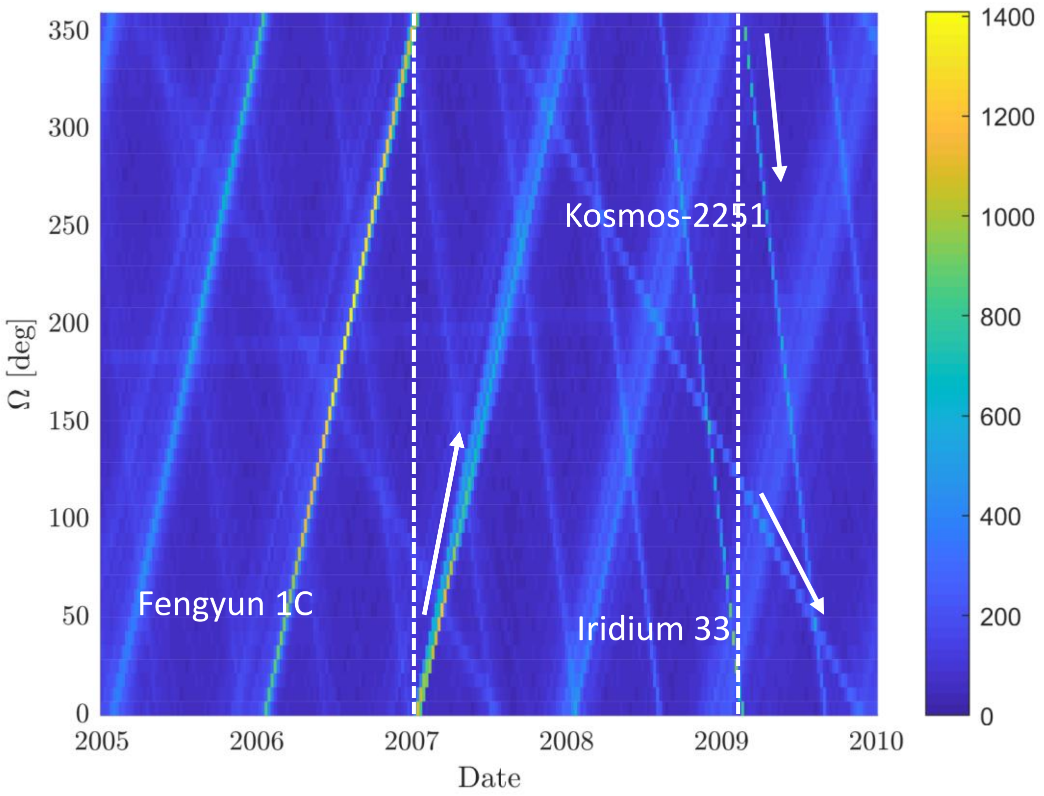
- *ESA Space Debris Office, ESA's Annual Space Environment Report. Technical Note, May 2018.*
- *ROSCOSMOS IADC 2018, (WG 1) Recent major fragmentation of Transtage 17 (1969-013B) in GEO*

Break-up localisation

Method

- Propagating back all fragments (**individually**) lead to peaks in the spatial density indicating break-up epoch and location
- However, ballistic coefficient estimation usually shows large variability, leading to inaccurate semi-major axis and eccentricity
- On the other hand, estimation of node and argument of perigee shown to be robust for several years
- Focusing (concentration) of node indicates break-up

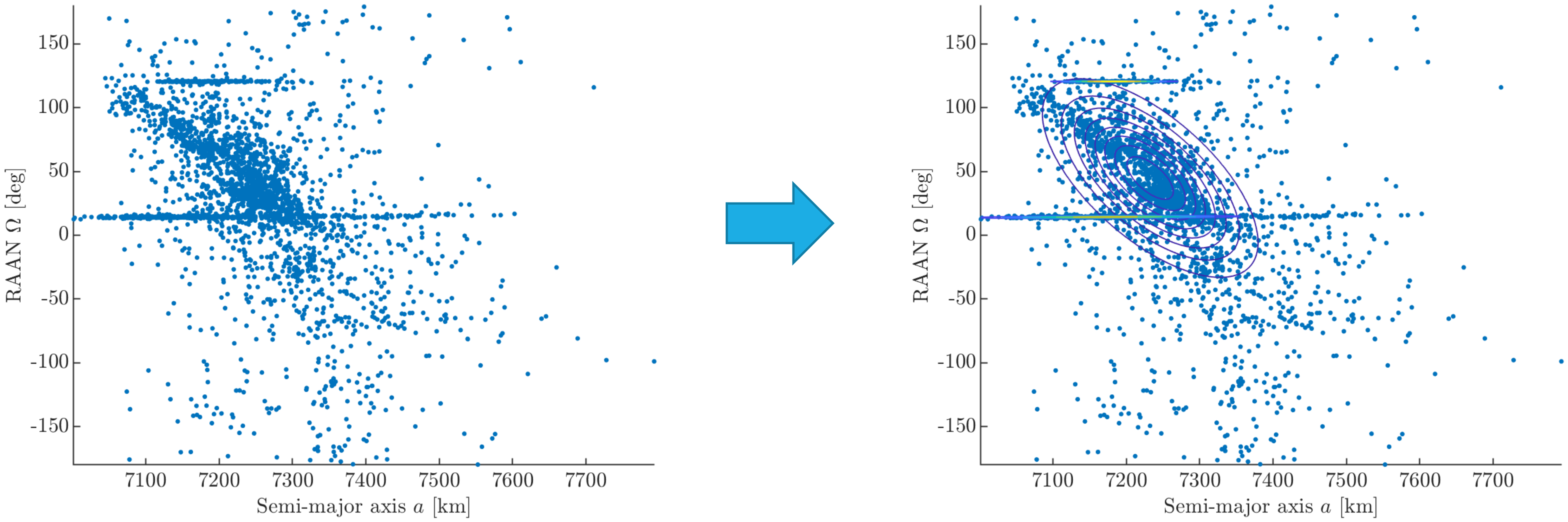
RAAN distribution, all fragments from 2010 back



Break-up localisation

Clustering, classification

- Statistical interference for identification of sources and subsequent assigning of probability, e.g. Gaussian Mixture Model depending on “orbit similarity”



Outlook

- Density based propagation to estimate the evolution of the space debris environment allowing to adapt to new fragmentations easily
- Ideally, together with a criticality index, this method would be employed in rating future space missions towards their compliance with the mitigation guidelines
- This rating could lead to go/no-go decisions, or mandate a more effective post-mission disposal

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 679086 – COMPASS)

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