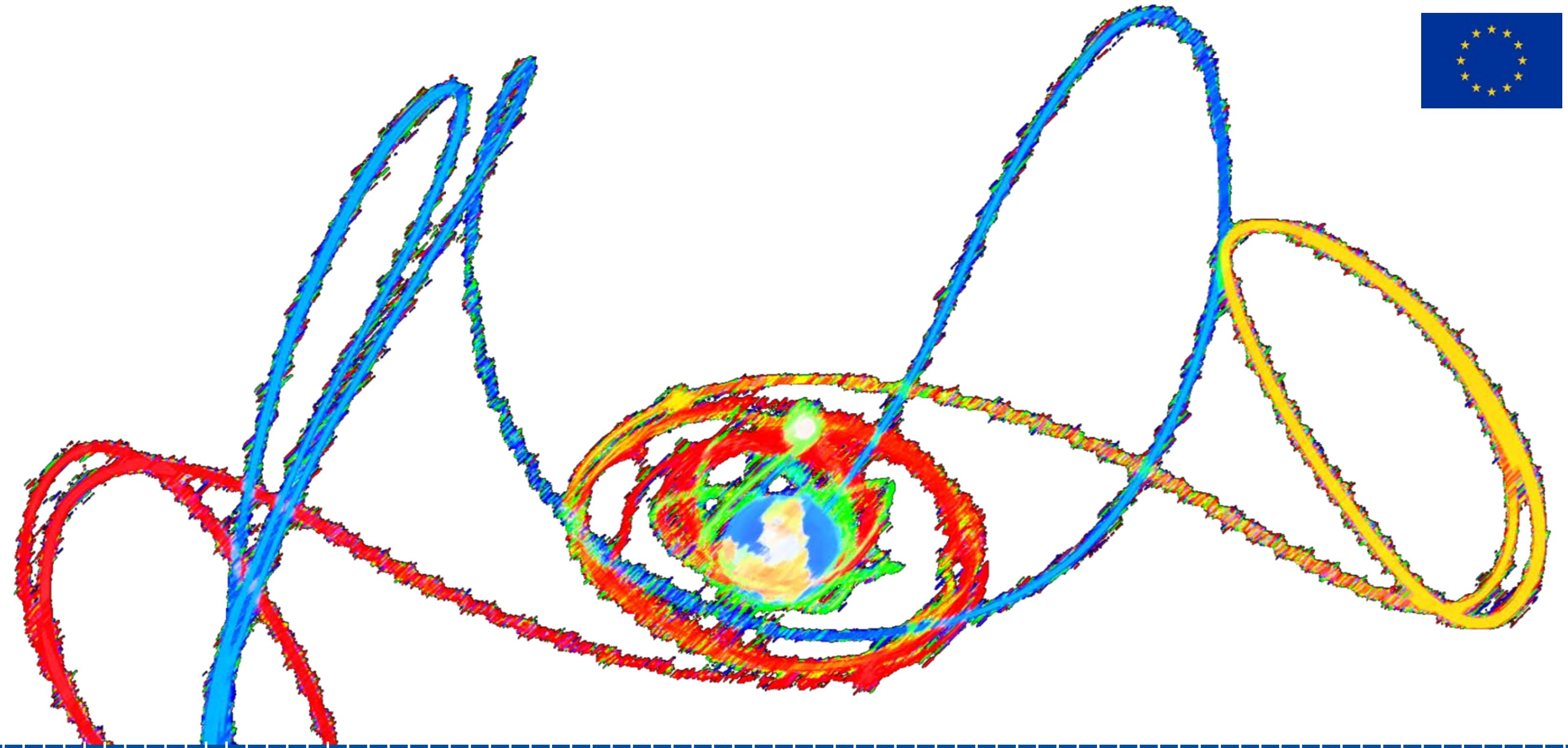

Density based modelling and indication of break-up location and epoch from fragments using backwards propagation

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

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DENSITY PROPAGATION

Introduction

Why a density-based debris model?

- Statistical collision risk estimation from objects down to very small sizes
- Required computational power independent of number of fragments
- Inherently statistical (no need of Monte Carlo runs, as e.g. for DELTA)
- Insight of cloud evolution
- Application to criticality index computation

Want to

- Generalise the existing cloud propagation methods to any orbital region
- Remove some simplifying assumptions (such as randomisation in certain variables)
- Broader application to space debris population propagation

- *F. Letizia, C. Colombo, H. G. Lewis. Analytical Model for the Propagation of Small-Debris-Object Clouds After Fragmentations. JGCD, 38(8):1478-1491, 2015.*
- *F. Letizia, C. Colombo, H. G. Lewis. Multidimensional extension of the continuity equation method for debris clouds evolution. ASR, 57:1624-1640, 2016*

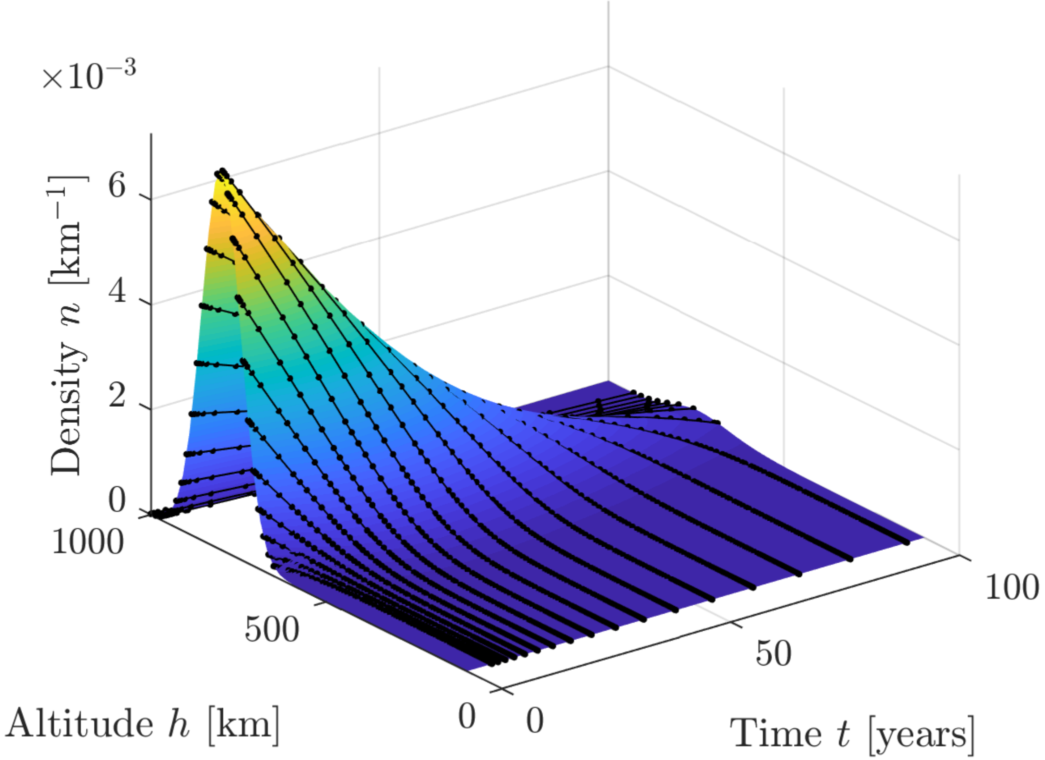
Density Propagation

Formulation

- Fragments cloud or environment as 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
- Possible phase space
  - Five Keplerian states $(a, e, i, \Omega, \omega)$
  - Physical properties $(\frac{A}{m}, c_d, c_r)$
- Can consider collisional feedback



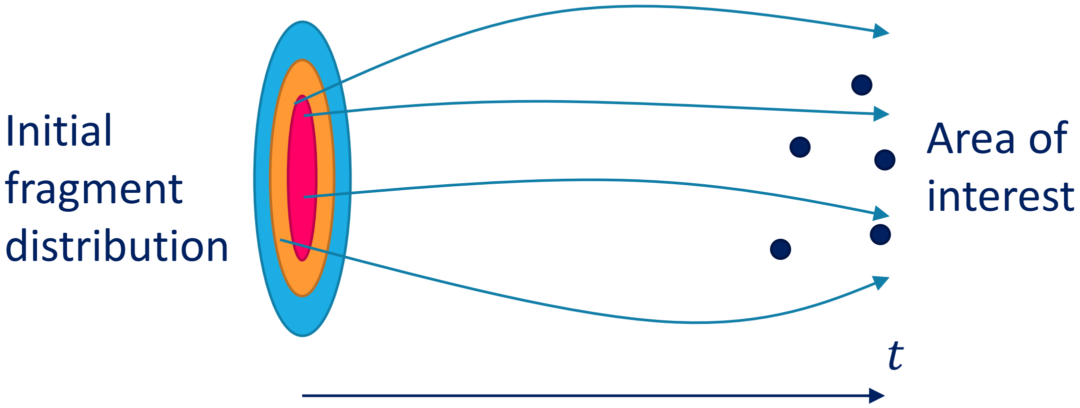
Density Propagation

Propagation method

Population-driven forward propagation

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

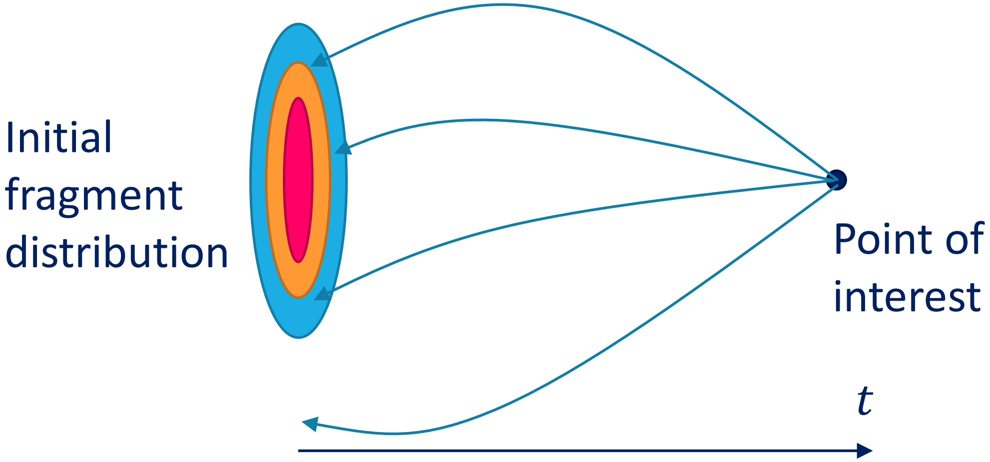
Ideal if density needs to be known at many points



Target-driven backward propagation

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

Ideal if high accuracy in density is required



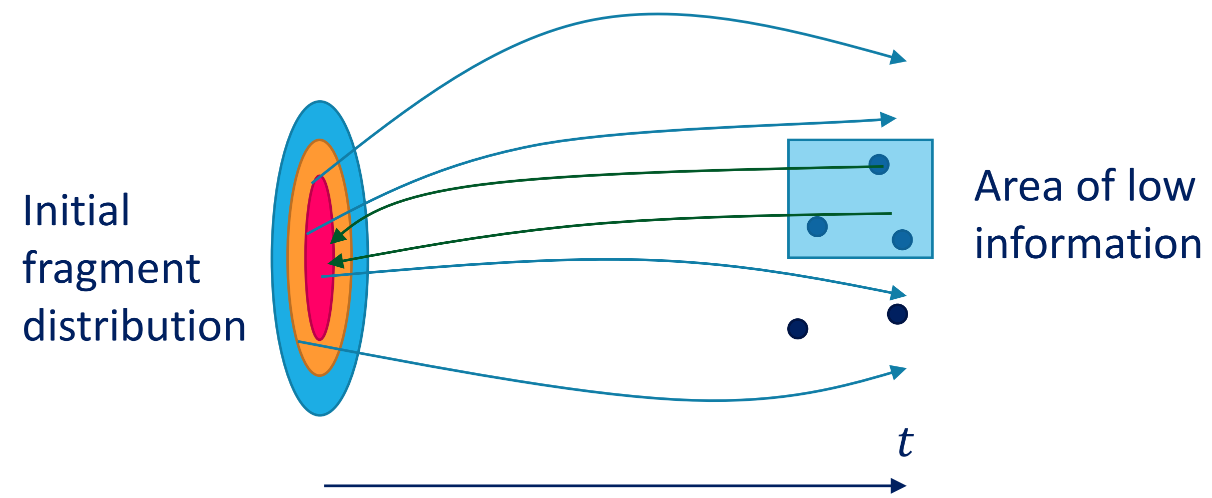
Density Propagation

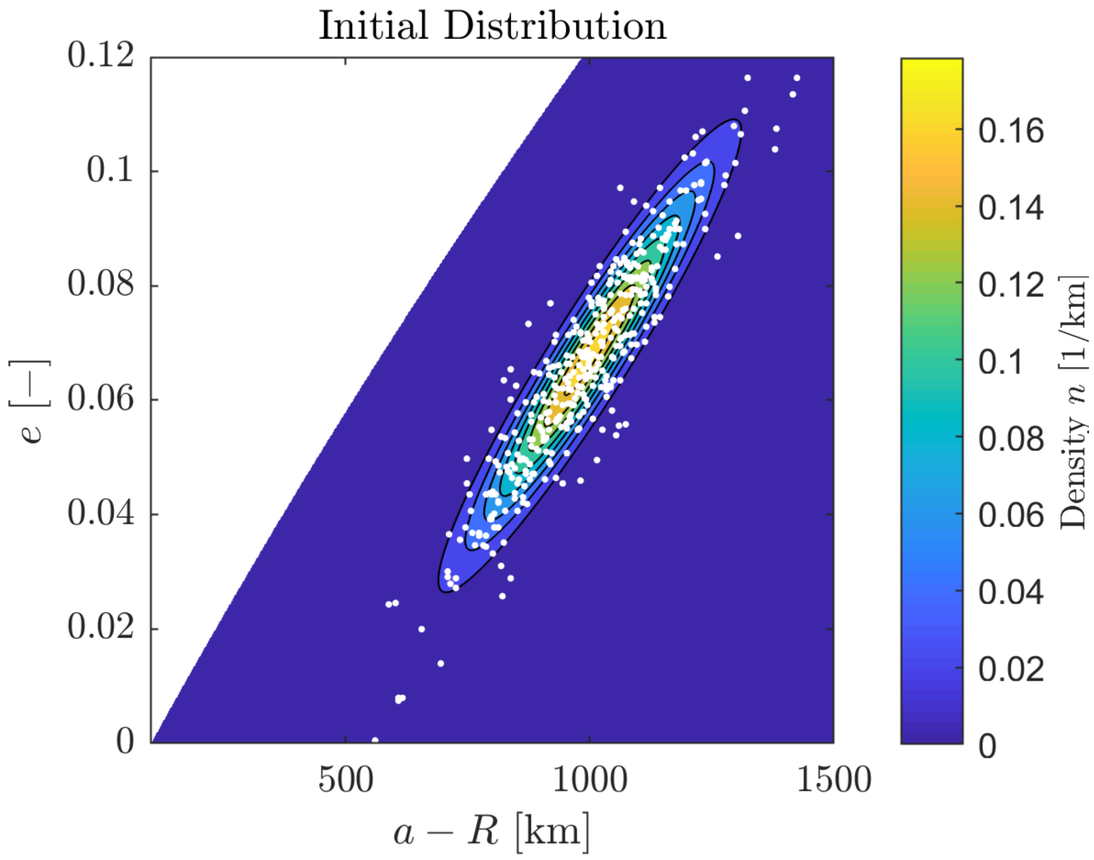
Initial points selection: Curse of dimensionality

Combination

Sample initial distribution, e.g. many points where density is high

Use combination of population-driven forward to identify the admissible region to be used for target-driven backward propagation



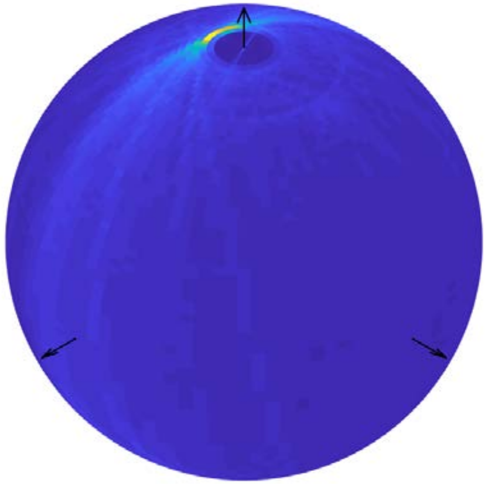


Density Propagation

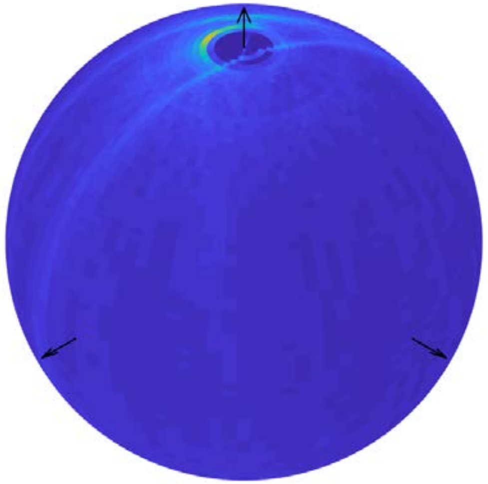
Building of initial condition of full environment model

- Initial condition for background population from observations and space debris environmental tools (e.g. ESA's MASTER)
- Initial condition for fragmentations from break-up models
- Convert into spatial density (averaged over one orbit) for graphical representation and collision risk estimations
- Peak in spatial density equals large number of fragments crossing same bin, indicating fragmentation

Spatial density from observed fragments in LEO



1 January 2008
4607 objects



1 January 2010
6047 objects

➢ *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.*

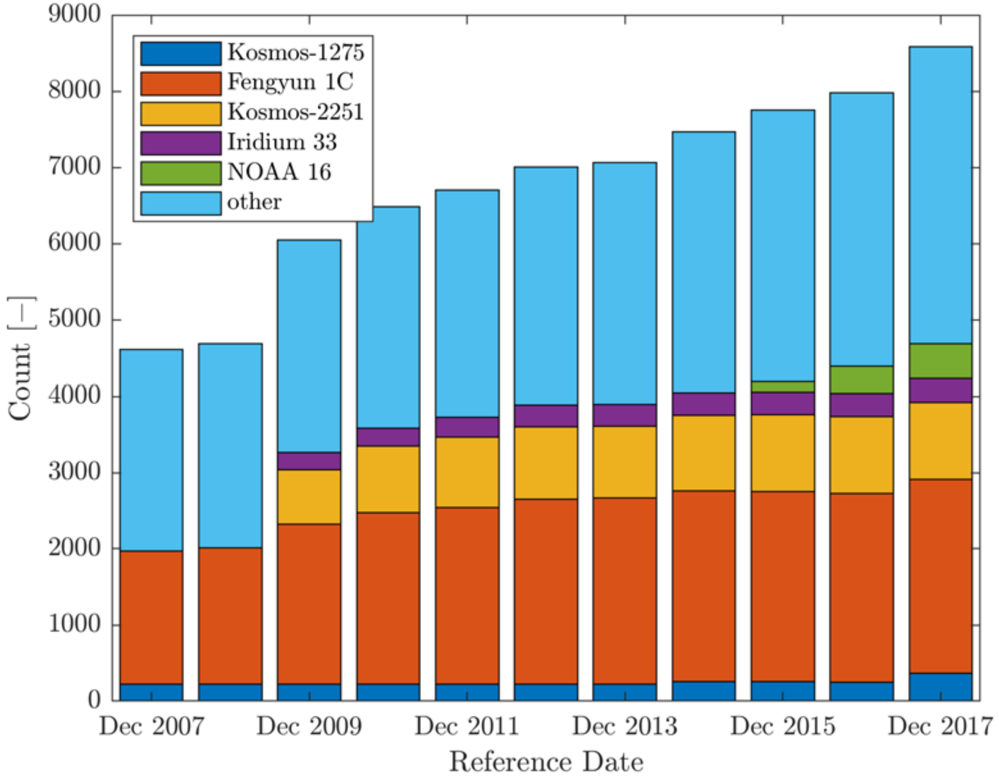
BREAK-UP LOCALISATION

Break-up localisation

Need

- Ever increasing observational capabilities (e.g. Space Fence) will add small fragments of unknown origin to the catalogue
- Already now, 2500 unidentified objects are tracked, mostly non-LEO
- Knowledge about fragment object
  - For liability reasons
  - Characterisation in terms of material
  - Could lead to unknown fragmentations
  - Pure interest

Observed Fragments in LEO



➤ *ESA Space Debris Office, ESA's Annual Space Environment Report. Technical Note, May 2018.*

Break-up localisation

Traditional approach and its limits

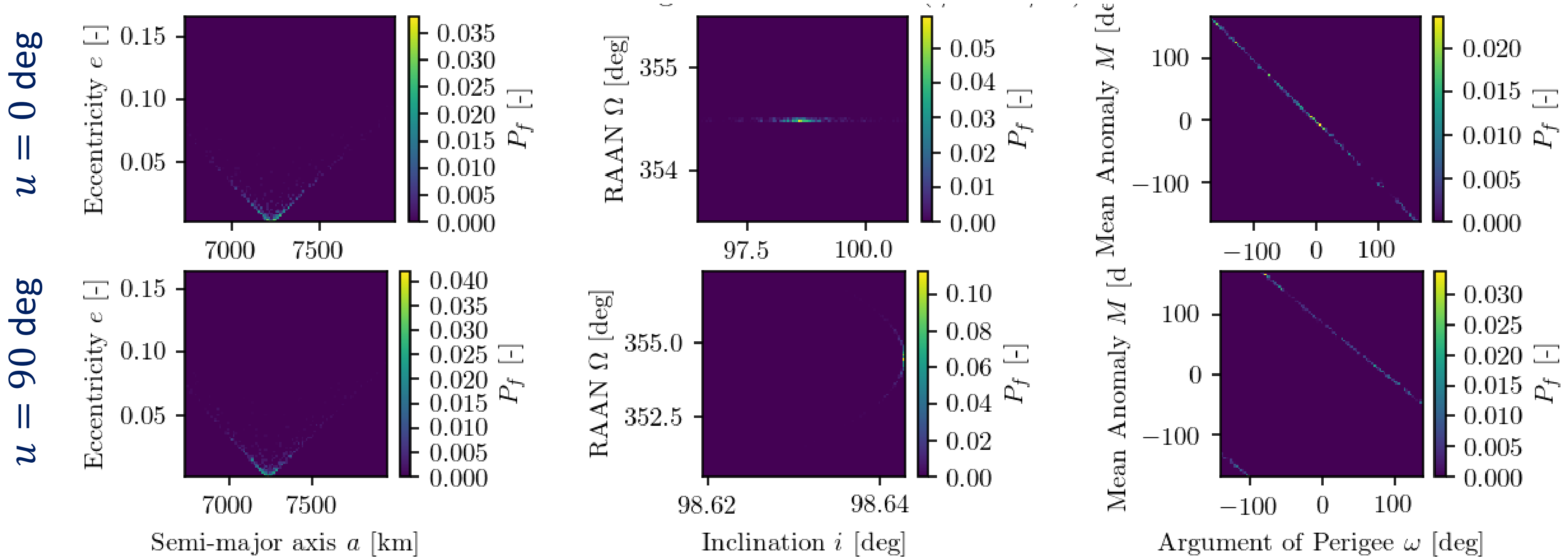
- In case of a fragmentation, new objects are observed and tracked after few passes
- Those objects can be propagated back a couple of orbits until the average separation (distance) between all the objects is at its minimum
- Requires good knowledge about the position of each fragment on its orbit
- But if generation event of newly observed and tracked fragments lies back several years, cannot accurately propagate back to parent object
- So origin can only be assigned probabilistically
- What are robust variables/features?
  - Look at distribution right after fragmentation
  - Find variables that can be accurately propagated given uncertainties

➢ *N. L. Johnson and D. S. McKnight. Articial Space Debris. Krieger Publishing Company, 1991.*

Break-up localisation

Expected break-up distributions in LEO

- According to the NASA break-up model, distributions in i and Ω remain bounded, even considering small fragments down to 1 mm



Spacecraft Explosion

$a = 7231$km

$e = 0.001$

$i = 98.6$ deg

$\Omega = 354$ deg

$\omega = 289$ deg

- In highly eccentric orbits, i/Ω spread increases slightly, however information about ω can be gained

➢ *N. L. Johnson, P. H. Krisko, J.-C. Liou, P. D. Anz-Meador, NASA's new breakup model of evolve 4.0. Advances in Space Research, 28:1377-1384, 2001*

Break-up localisation

Propagator

- Semi-analytical propagator PlanODyn as many fragments need to be propagated **individually** for several years
- Very simple force model as in this study only LEO fragments are considered
  - Oblate gravitational field, J_2
  - Drag forces through temperature dependent, smooth exponential atmosphere model (fit to Jacchia-77)
- Estimates for ballistic coefficients taken from ESA's DISCOS
  - Estimated through FOCUS-1k (different force model!)
  - Typical fitting window 110 days, shooting method

➢ *C. Colombo. Planetary Orbital Dynamics (PlanODyn) suite for long term propagation in perturbed environment. In Proc. of 6th ICATT, 2016*

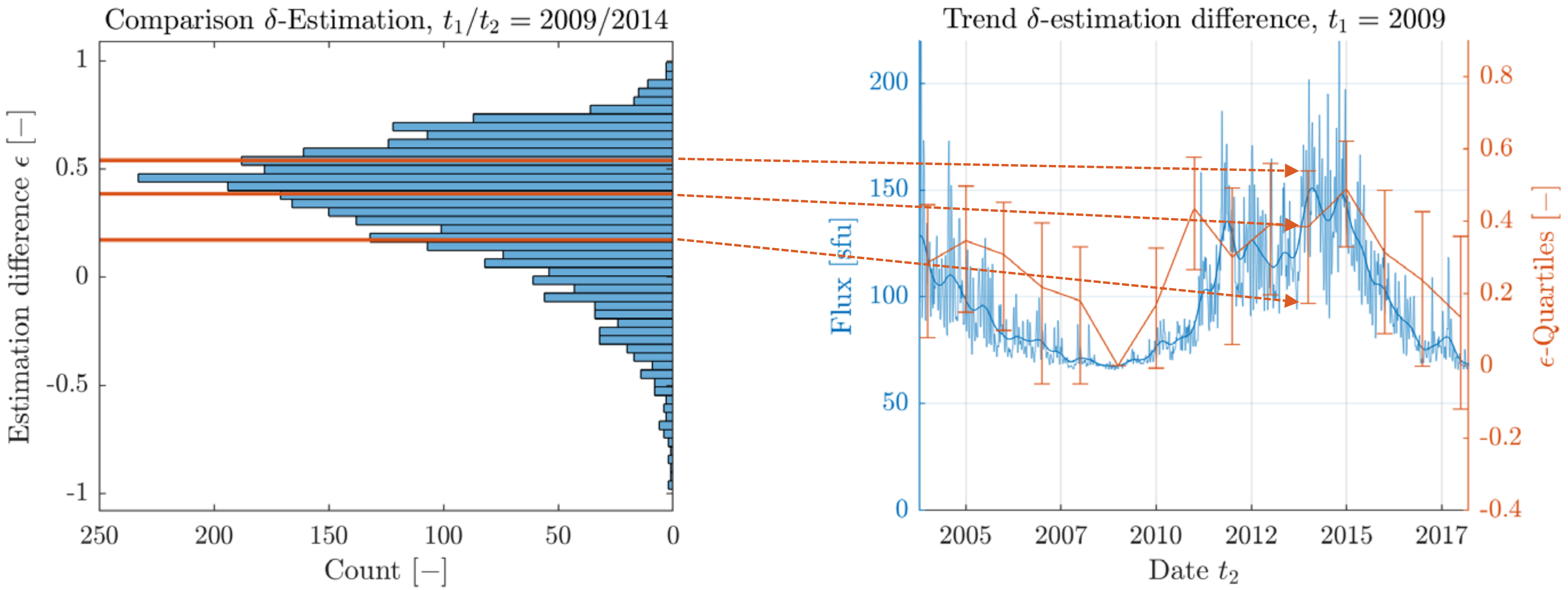
Break-up localisation

Uncertainty in BC estimates

- Large uncertainties in ballistic coefficient estimation depending on time of fit
- Correlating with 11-solar cycle despite consideration of flux during estimation process

$$\delta = BC^{-1} = c_d A/m$$

$$\epsilon = \frac{\delta(t_2) - \delta(t_1)}{\max\limits_{t_1,t_2} \delta(t)}$$



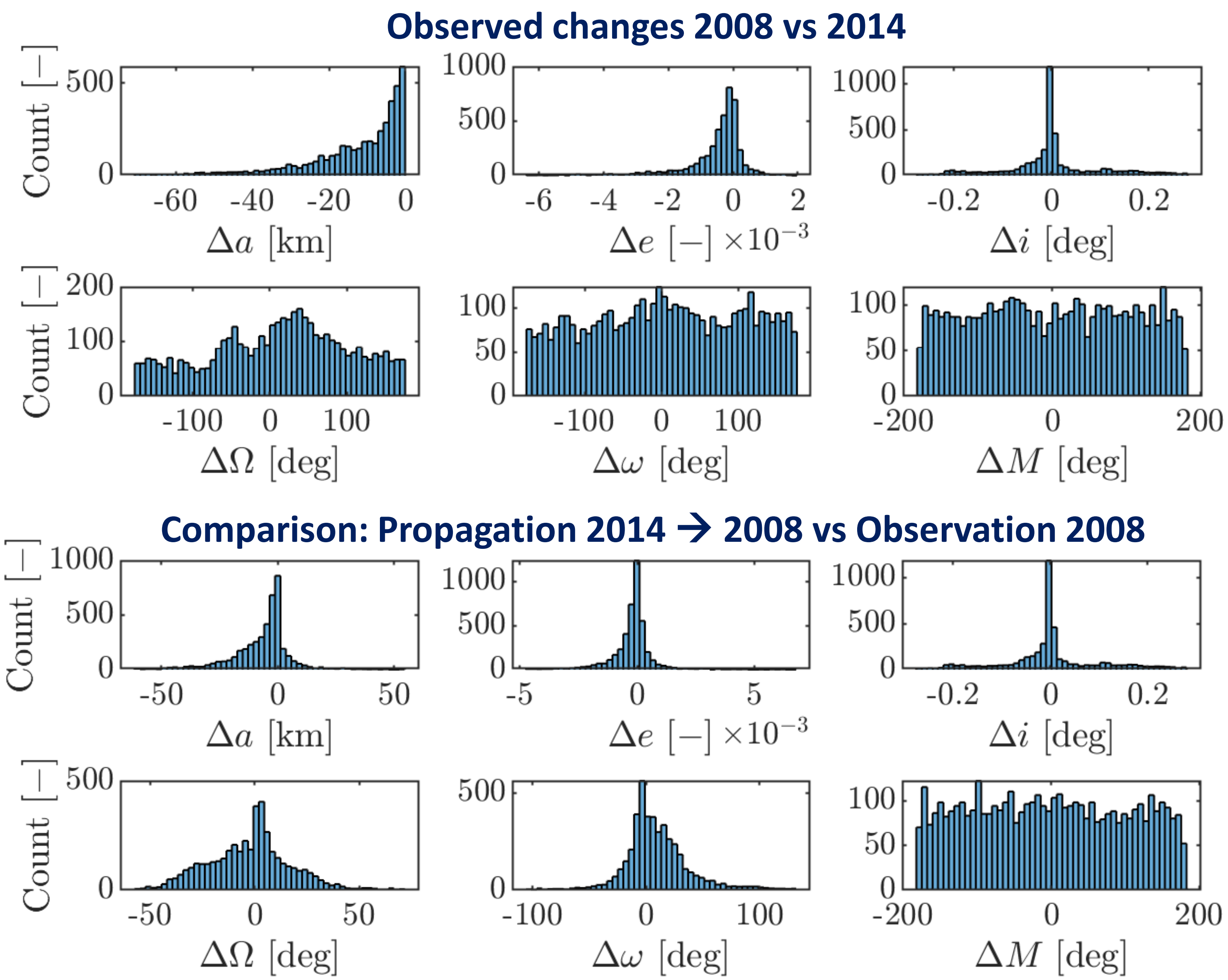
- Conservative approach: very limited knowledge about ballistic coefficient

➢ *H. Klinkrad, Space Debris: Models and Risk Analysis, Springer-Verlag, United Kingdom, 2006.*

Break-up localisation

Propagator Validation

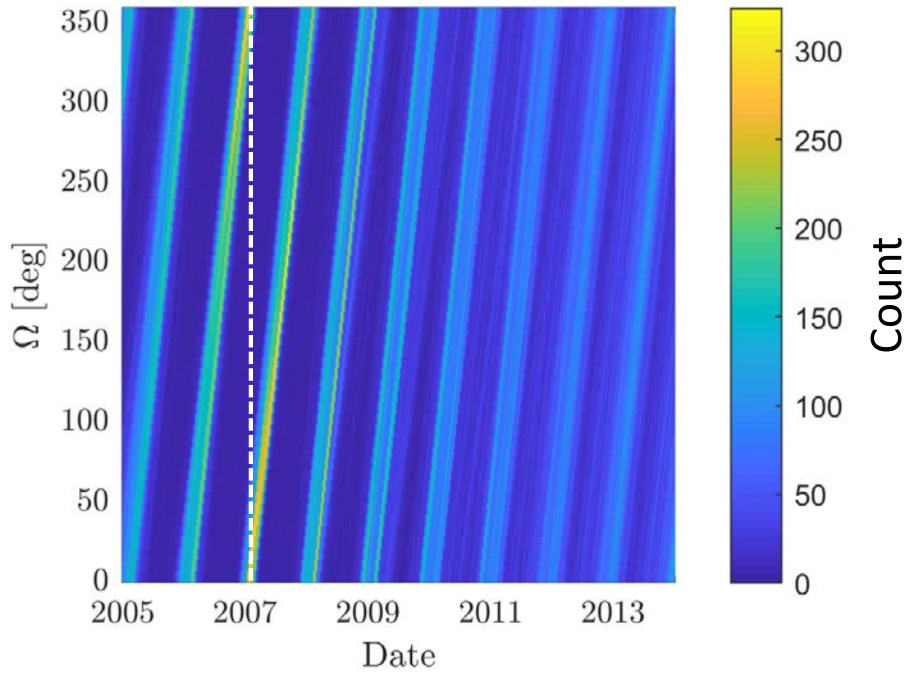
- Propagating back all LEO fragments from 2014 to 2008
- Unsurprisingly, bad estimates in a and e, errors in the order of change over time
- Still, decent approximations of states in i, Ω and ω, e.g. sun-synchronous orbit (SSO) and six years propagation equals nodal precession of 2160 degrees
- Can use i and Ω as features in LEO



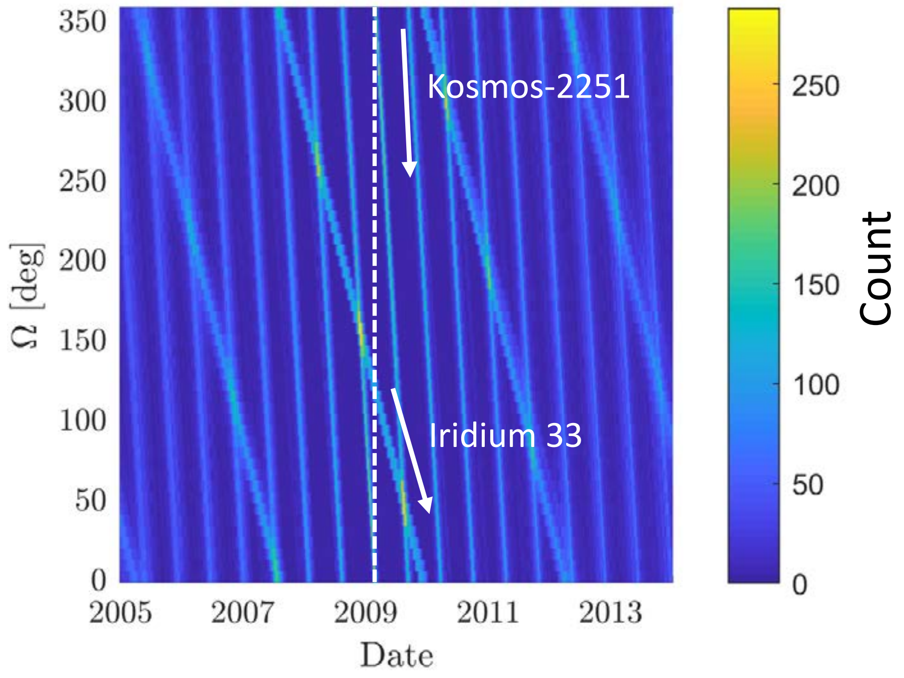
Break-up localisation

Examples: Backpropagating LEO fragments

- Fengyun 1C fragments originating from January 2007



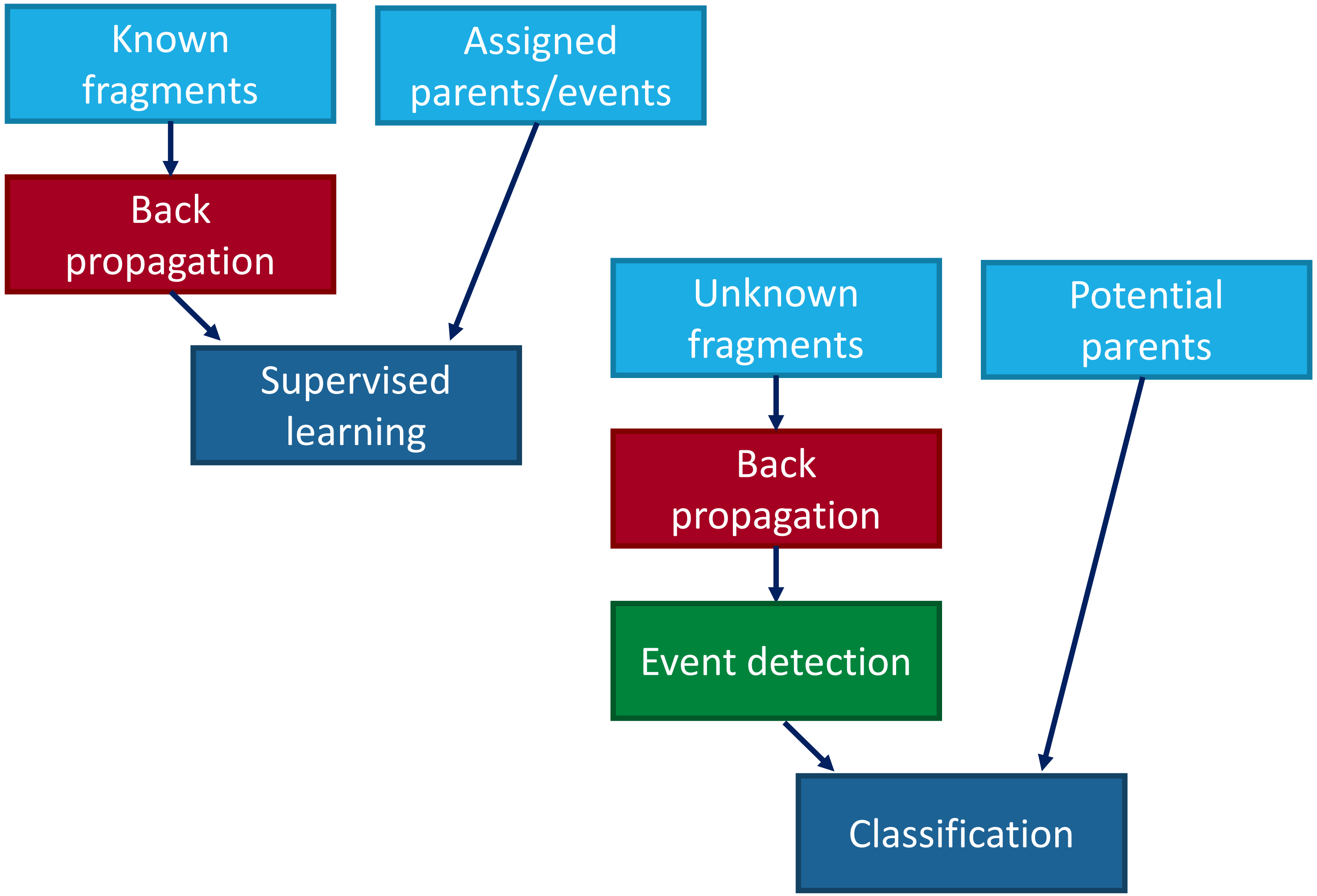
- Kosmos/Iridium fragments originating from February 2009



Break-up localisation

Method: Supervised Learning

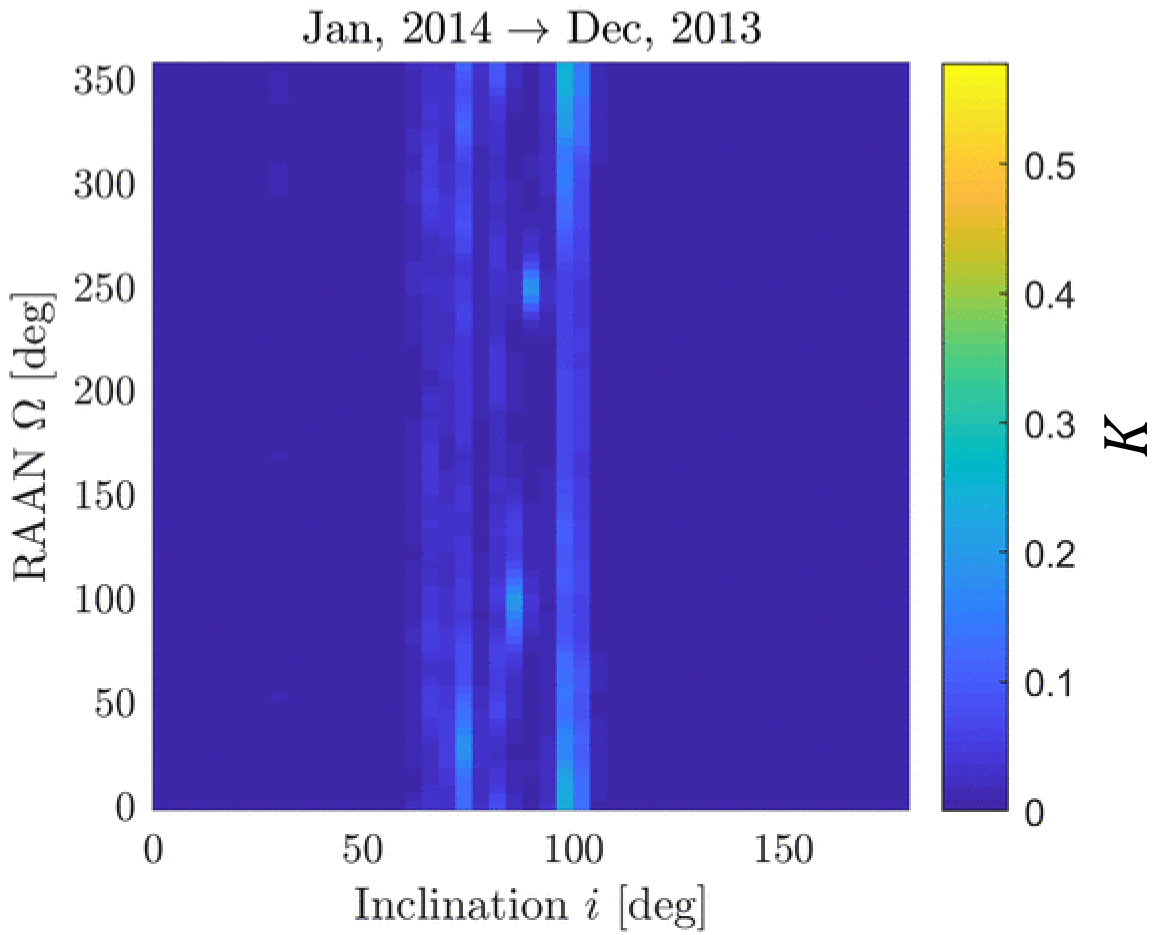
- Propagate back known fragments to events
- Train supervised learning algorithm by pairing with parent objects using robust features
- Propagate back all unknown fragments until…
- Event detection: focusing (concentration) of node indicating break-up
- Classify unknown fragments probabilistically using trained algorithm



Break-up localisation

Event detection

- E.g. all LEO fragments, propagated backwards from 2014 to 2005
- Using Gaussian filter together with a circular von Mises distribution in Ω
- Weighted to highlight regions with less fragments



Break-up localisation

Supervised learning

- Statistical interference for identification of sources and subsequent assigning of probability, depending on “orbit similarity”
- Flexible classifier needed, as shape of fragment distribution in Keplerian elements depends largely on type of fragmentation, orbit and location on orbit
- Training data in the form of correlated objects available
- Problems
  - Available learning data possibly biased towards “easily trackable and identifiable”, e.g. lack of small high area to mass ratio fragments
  - Not plenty of learning data nor unrestricted access to unidentified objects available

Conclusion

Density based approach

- Estimation of space debris environment with quick adaption to new fragmentations
- Ideally, together with a criticality index, this method would be employed in rating future space missions towards their influence on the capacity

Parent identification

- Robust features as well as training data available
- Verify if non-LEO fragments can be accurately propagated backwards
- Need to find a good learning algorithm to classify fragments

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