FROM END-OF-LIFE TO IMPACT ON GROUND

AN OVERVIEW OF TOOLS AND TECHNIQUES TO PREDICTED RE-ENTRIES

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Re-entry Prediction Service

- There are about 17 000 tracked objects in Earth orbit:
  - ~ 7500 have an estimated orbital lifetime less than 100 year.
  - ~ 1250 of those have a mass of more than 1 kg
  - Vast majority are smaller pieces of space debris.
- An automatic service has been in use since 1999 to provide re-entry predictions (daily) for all the objects:
  - As 10 to 40 % of large objects such as rocket bodies or satellites can survive until ground impact.
  - As we are interested in the statistical decay rates for environment evolution.
  - Intimately linked with orbital lifetime predictions prior to launch.
  - Considering atmospheric and third-body induced re-entries.
- The focus is on the service as a whole, not the individual object!

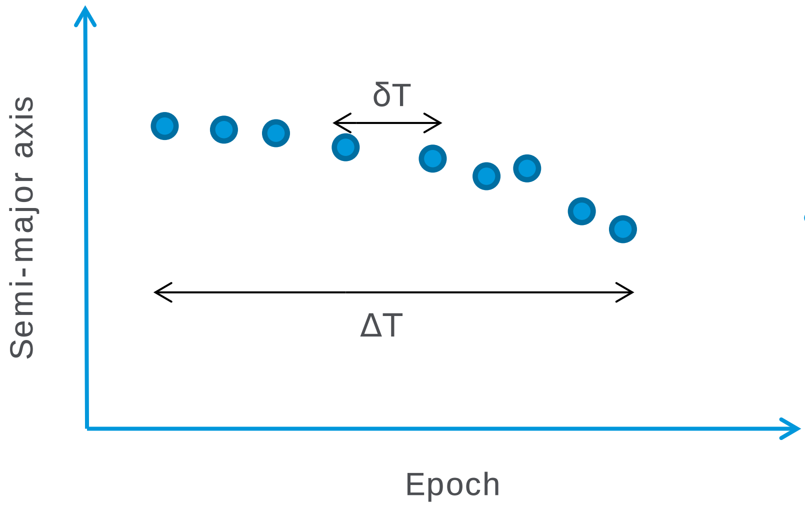
Re-entry Prediction Service

- Environment model:
  - Solar and geomagnetic activity prediction model (SOLMAG) for the solar proxies (Sun spot number, F10.7, daily Ap):
    - Short term prediction (solar day, ~ 1 month) based on a neural network
    - Long term based on McNish and Lincoln predictions for the sun spot numbers with correlations for F10.7 and Ap.
  - ISO and ECSS space weather methodologies supported.
  - Atmosphere model MSIS90, with bridging in lower altitudes.
- Input data:
  - Public Two-Line Element set provided by USSTRATCOM.
  - Dedicated observations near re-entry.
  - Catalogue on high eccentric objects (ISON).

Ballistic parameter estimation

- Derivation of the Ballistic parameter $B = c_D \frac{A}{m}$ key for the prediction accuracy.

- Based on a shooting method:



- δT parameter to describe the minimum time distance for state pairs.

- ΔT parameter to describe the time span for considering states for the *B* estimation.

Ballistic parameter estimation

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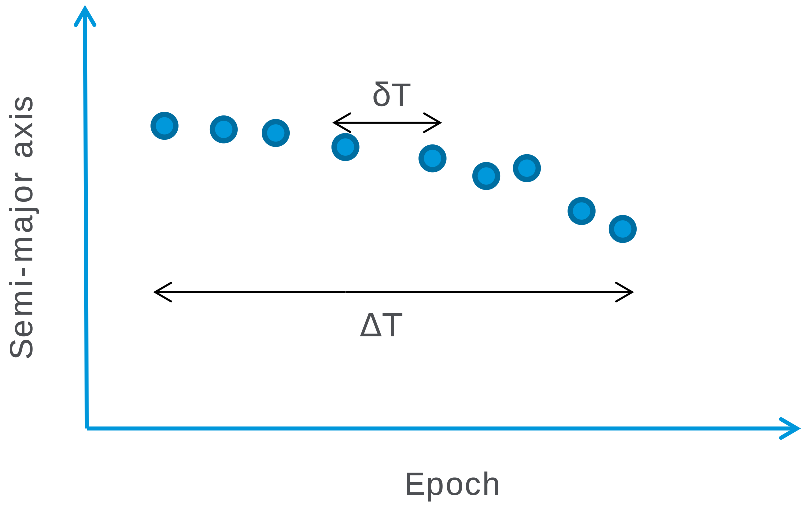
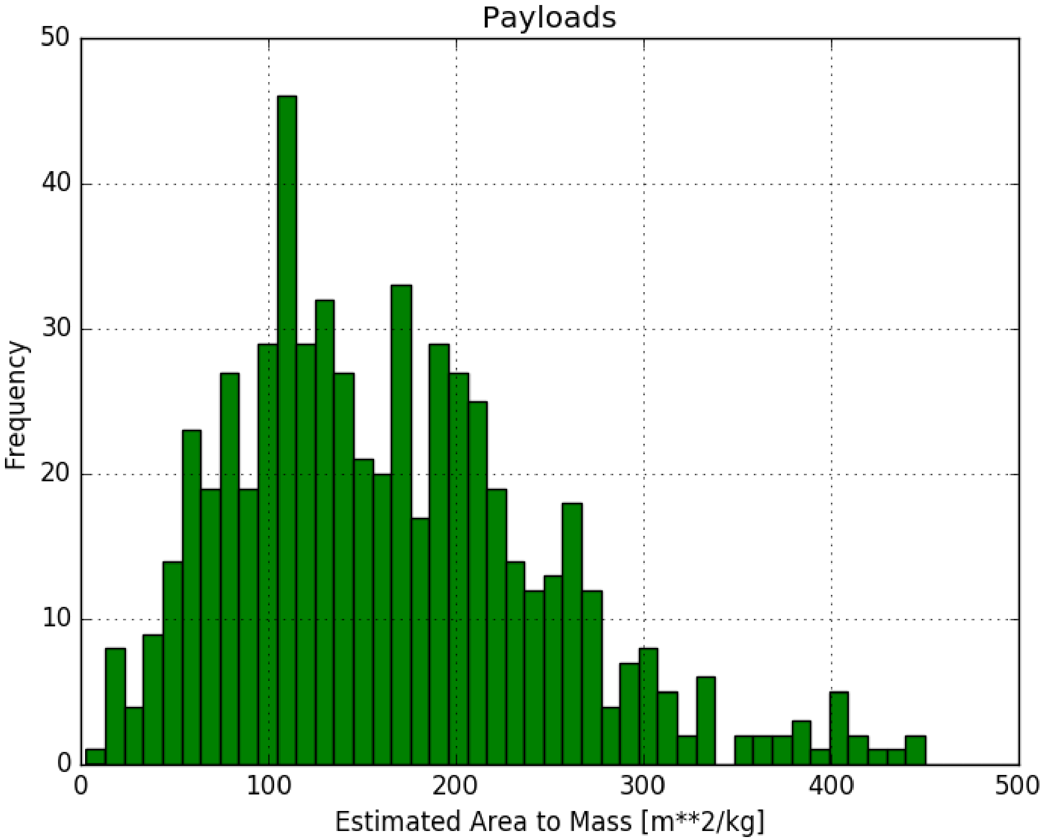
- Based on a shooting method:

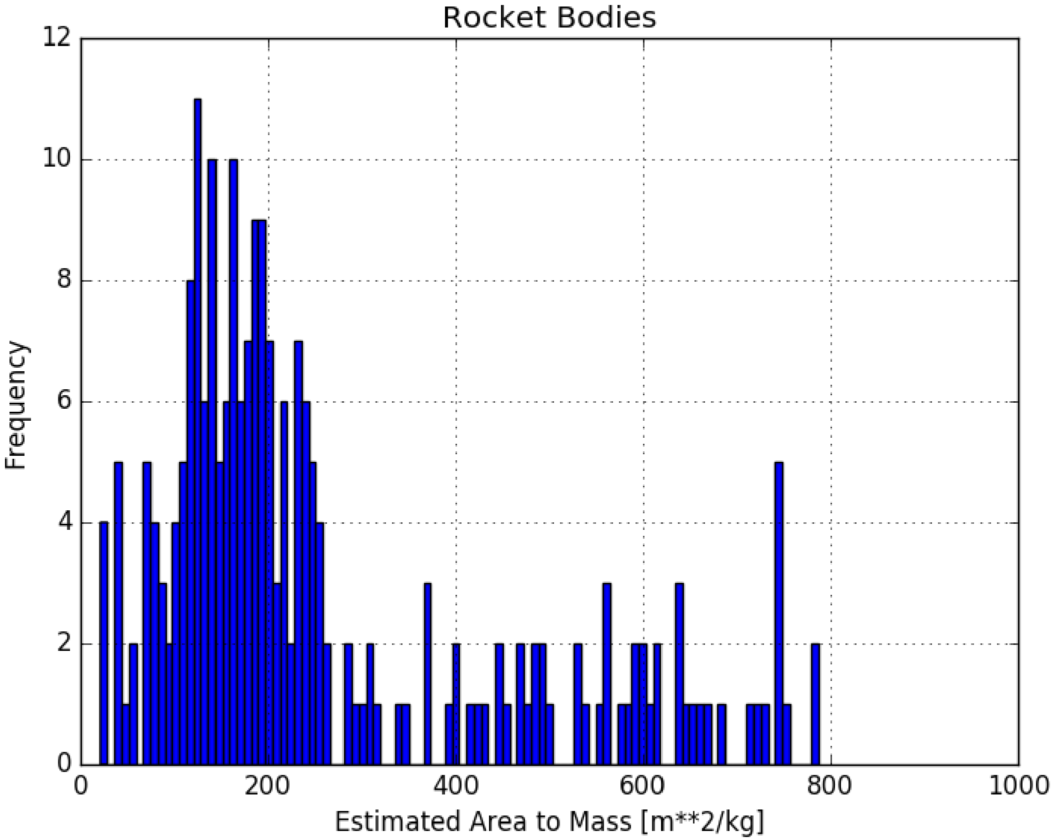


- For each pair, *Bp* minimised via a semi-analytical propagation which searches for the minimum positional error.
- Input is a geometric estimate (DISCOS).
- The mean of all pairs *Bps* is taken as estimated *B*.
- The variance can be used to identify manoeuvring objects.

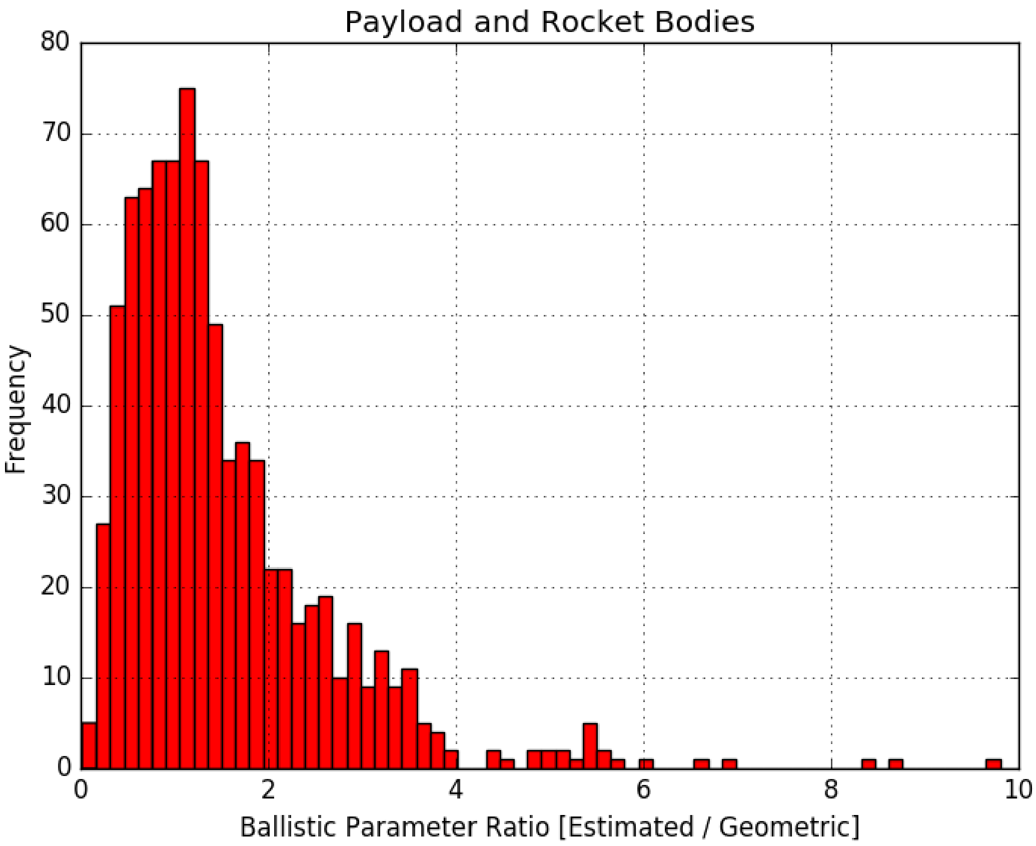
Ballistic parameter estimation



Ballistic parameter estimation



Ballistic parameter estimation



Ballistic parameter estimation

- Derivation of the Ballistic parameter $B = c_D \frac{A}{m}$ key for the prediction accuracy, as the propagation assumes 3 degrees of freedom:
    - Based on a shooting method, but there is a critical dependency on δT and ΔT.
    - Based on the results of an orbit determination process, in which case also the solar radiation pressure can be used.
    - Using the geometric derivation, e.g. in cases where the perigee altitude is above 1000km.

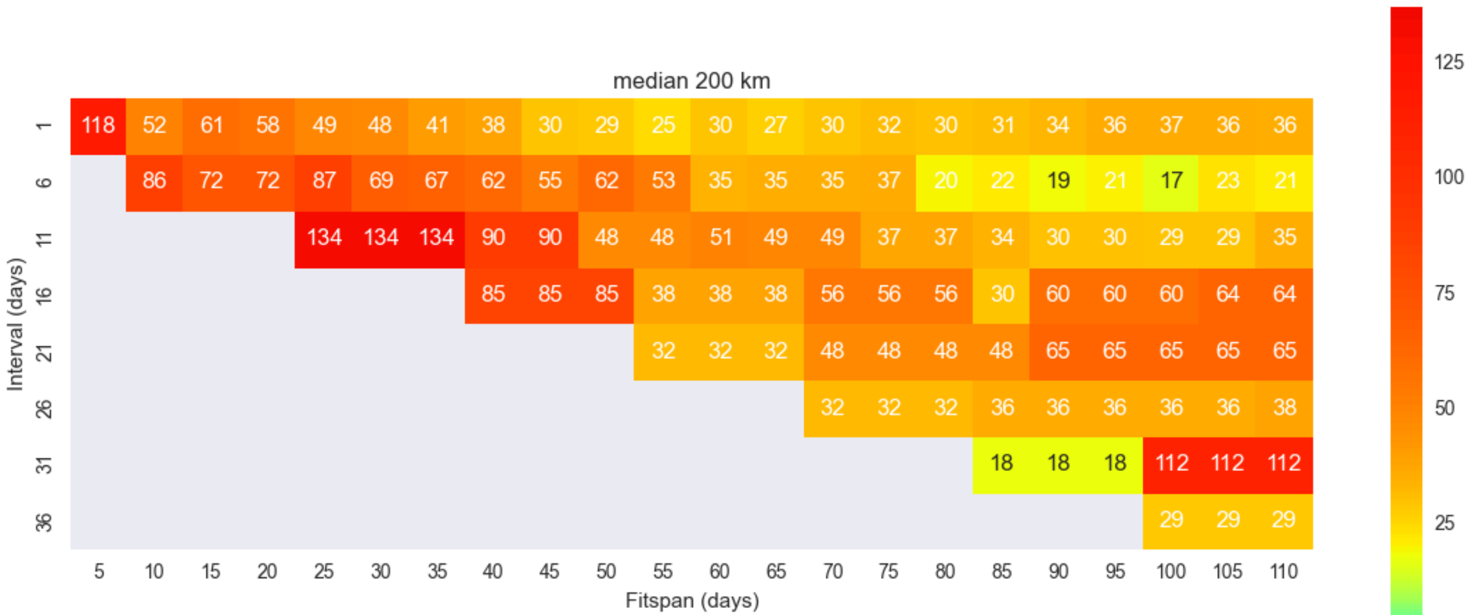
Ballistic parameter estimation

- As quality metric we can use the Relative Prediction Error:

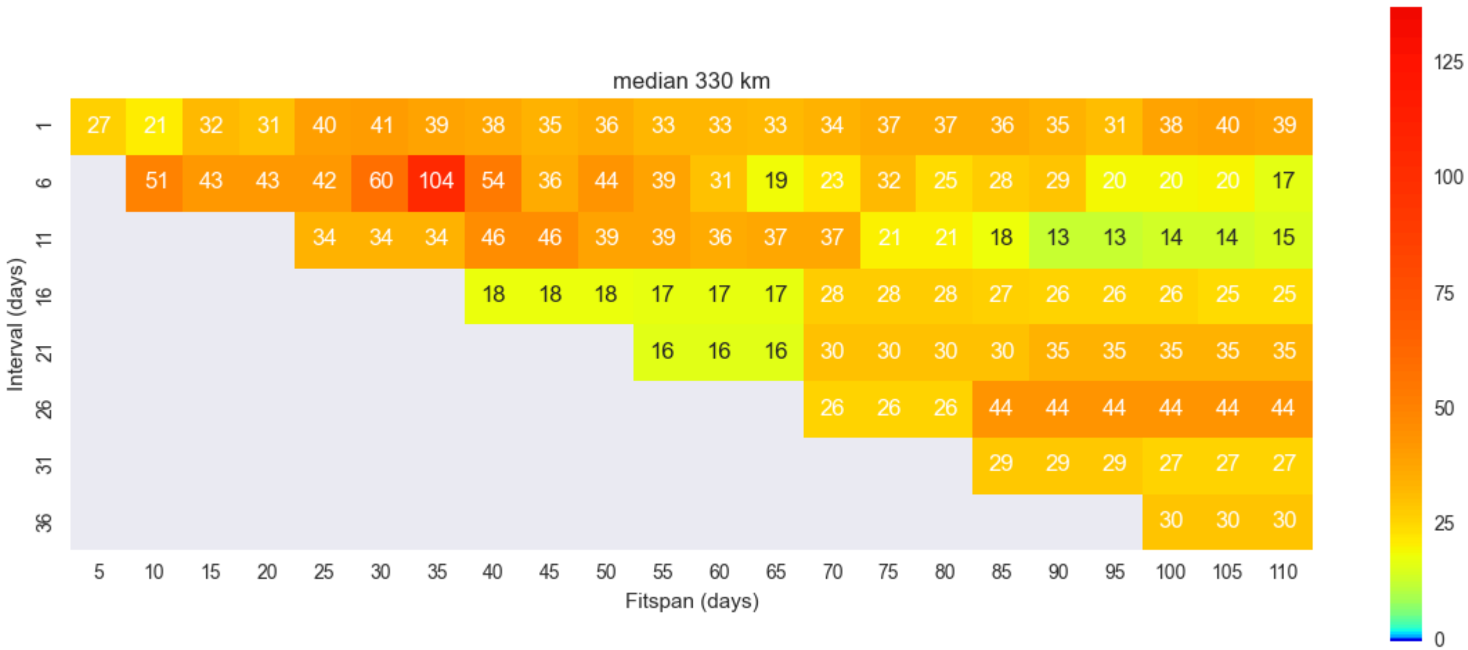
$$E_P = \left| \frac{Epoch_{predicted\ re-entry} - Epoch_{actual\ re-entry}}{Epoch_{prediction} - Epoch_{actual\ re-entry}} \right| \cdot 100$$

- By using a large group of objects in similar orbit regions, optimum solutions can be envisaged:
  - Nearly identical design, varying orbital node, none or limited variability in properties, availability of frequently updated orbital states.
  - Flock satellites released from the ISS (inc 52, circular, low alt)
  - Ariane upper stages in GTO

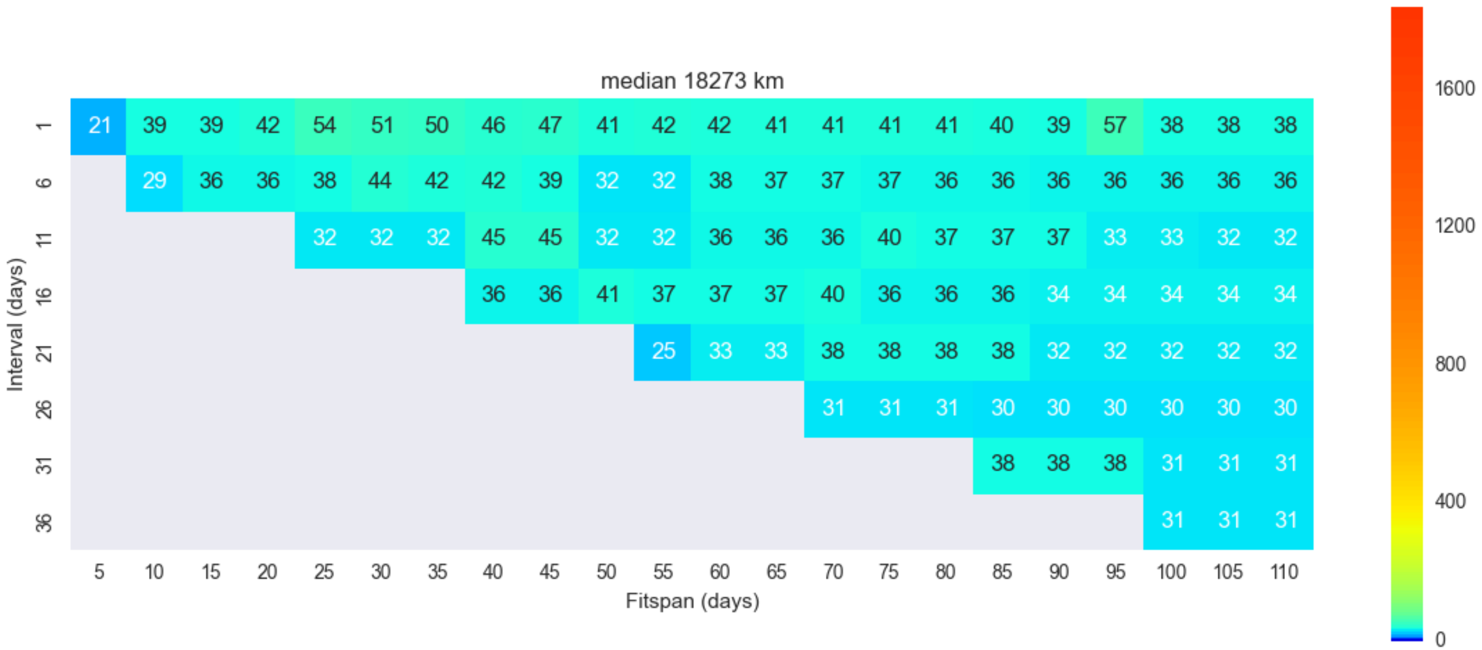
Ballistic parameter estimation: Flock



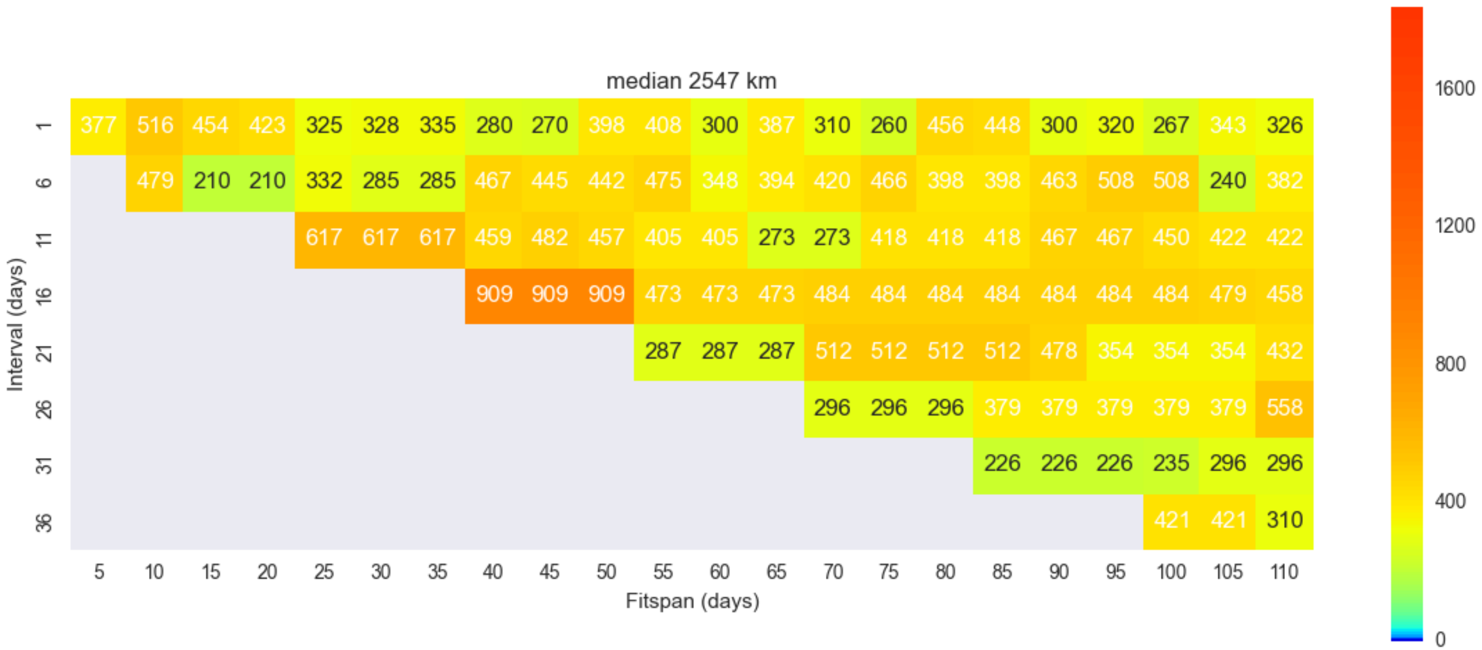
Ballistic parameter estimation: Flock



Ballistic parameter estimation: GTO

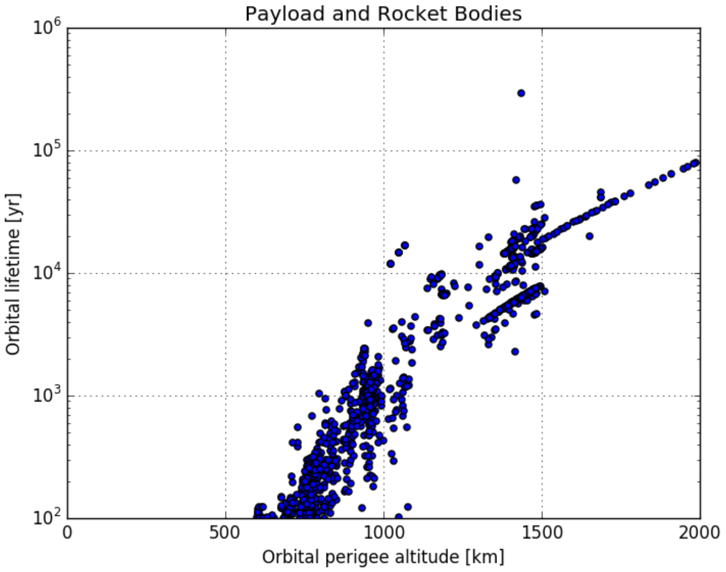


Ballistic parameter estimation: GTO



Long term re-entry prediction

- Analytic re-entry predictions as a first step for any object based on King-Hele equations (with density at initial perigee).
- This is it for objects for objects with a lifetime above 1000y.
- Iteratively (with density sampled at over solar cycles) applied to objects with a lifetime above multiple solar cycles.

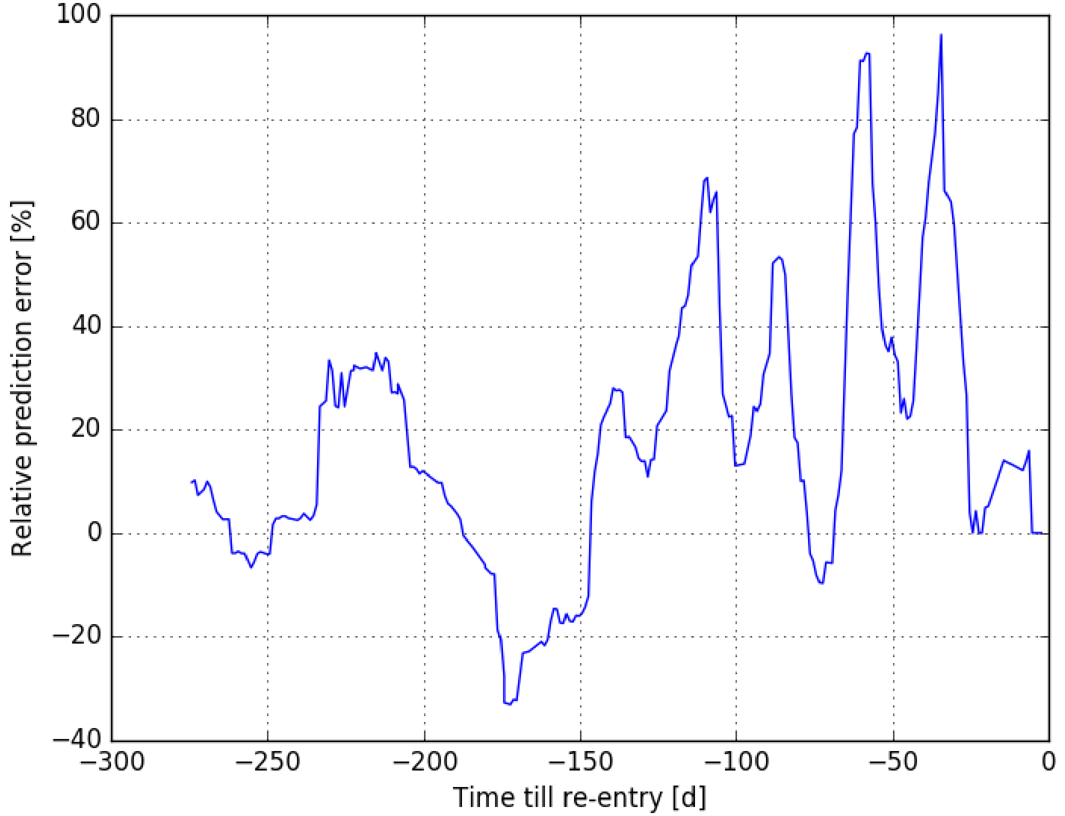


Short term re-entry prediction

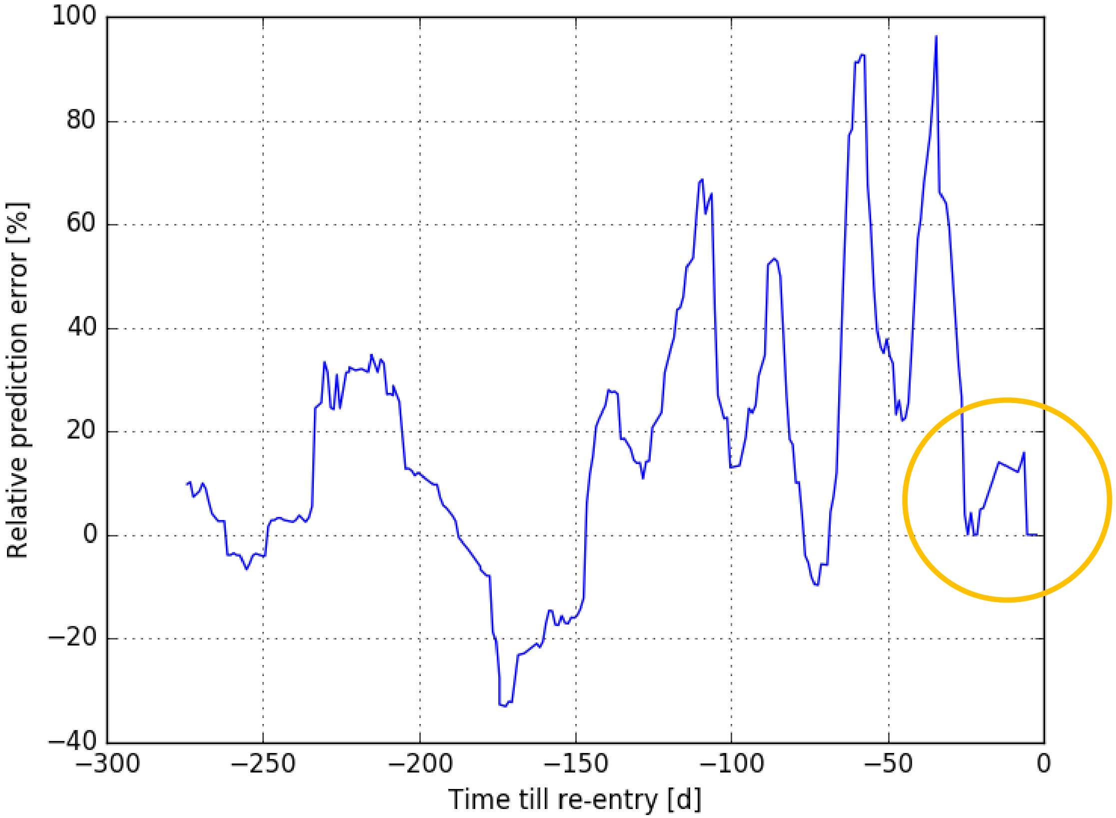
- For lifetimes less than two solar cycles and GTO objects.
- For an automated procedure, the aim is to have a qualitative assessment of the re-entry epoch.

- Fast Orbit Computation Utility Software (FOCUS):
  - Integrated combined time rates of change of singly averaged perturbation equations, taking into account a non-spherical Earth gravity potential, a dynamic Earth atmosphere, luni-solar gravity perturbations, and solar radiation.
  - Fourth-order Adams-Bashforth-Moulton predictor/corrector method, which is initiated by a self-starting fourth-order Runge–Kutta–Fehlberg method
  - Fixed time steps of 0.1 to 5 orbits, depending on the time to go until re-entry.

Short term re-entry prediction: automatic FOCUS example S3M



Short term re-entry prediction: automatic FOCUS example S3M

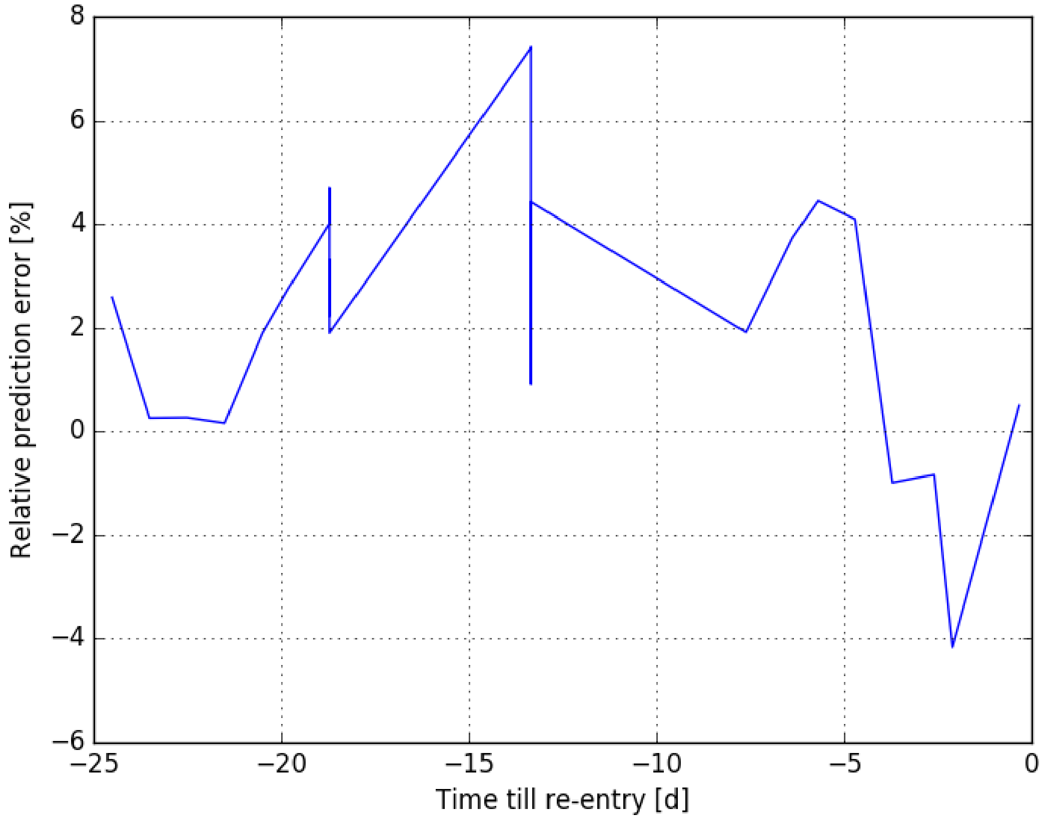


Short term re-entry prediction

- For lifetimes less than two solar cycles and GTO objects.
- For an automated procedure, the aim is to have a qualitative assessment of the re-entry epoch.
- Near the re-entry epoch of high interest objects this is replaced by manual re-entry predictions, with as aim the identification of the affected areas on ground.
    - $\pm 20\%$ E_P is considered state of the art.
    - Dedicated observation can be added.

- FOCUS/Orbit Generator (OrbGen) combination:
    - *B* estimation for the orbit determination process.
    - Full numerical integration when changing flow regimes.

Short term re-entry prediction: Dedicated prediction example S3M

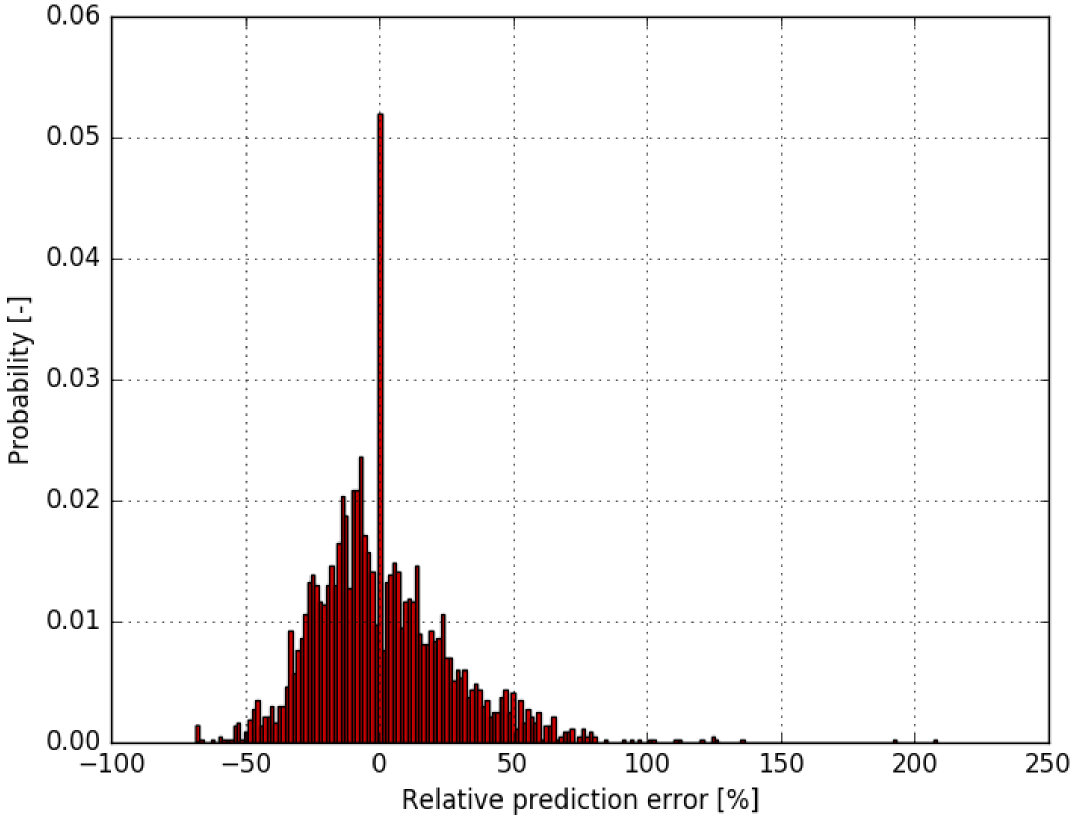


Short term re-entry prediction

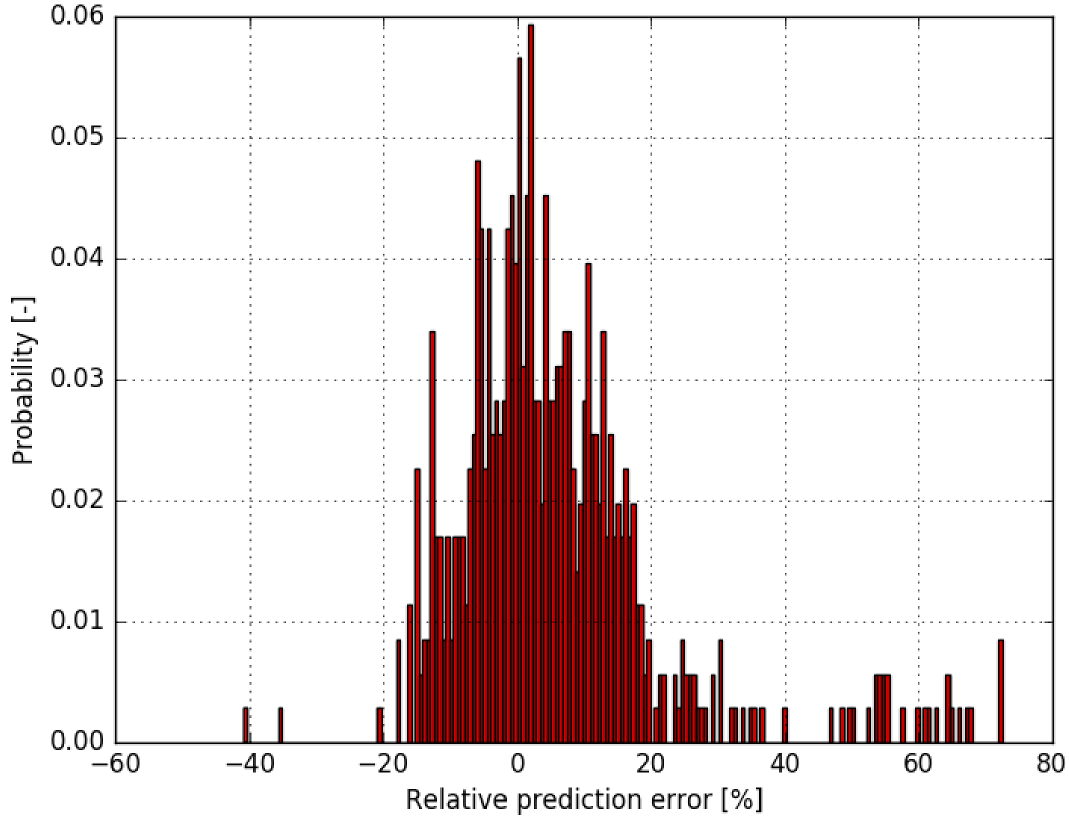
- To which extend is the calculation part, excluding the orbit determination, automatable?
- Can we reach the state of the art ±20% E_P (at least statistically)?

- FOCUS/Orbit Generator (OrbGen) augmented combination:
  - *B* is again estimated by a shooting method and refined based on minimisation w.r.t. to the semi-major axis and argument of latitude.
  - Full numerical integration when changing flow regimes.
- Comparison with assumed to be observed re-entry events (JSpOC data between 2014 and 2016) in terms of E_P:
  - payloads and rocket bodies, closer than 50 days till re-entry:
  - 62 objects, ecc < 0.01, for automatic prediction,
  - 25 objects for the augmented prediction.

Short term re-entry prediction: E_P automated predictions



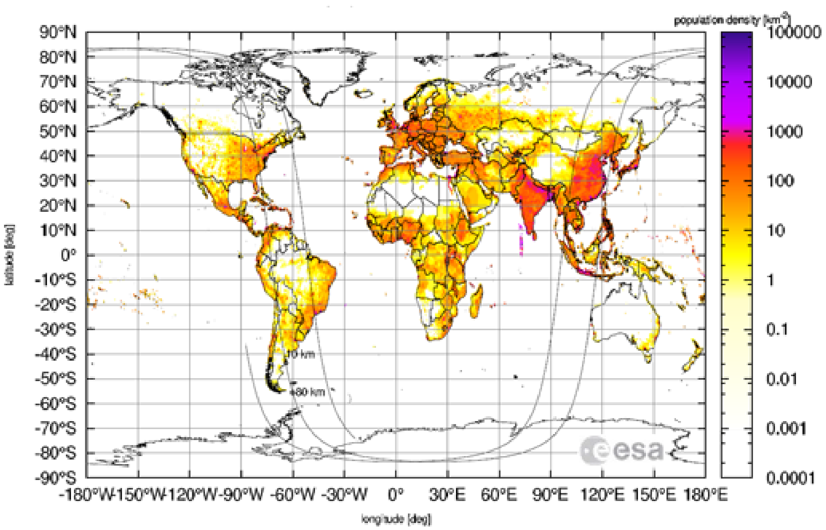
Short term re-entry prediction: E_P augmented predictions



Short term re-entry prediction

- Augmented but automated re-entry predictions stay within the ±20% E_P (at least circular ones).

- The existence of a general distribution function would imply a less conservative risk estimate during re-entries.



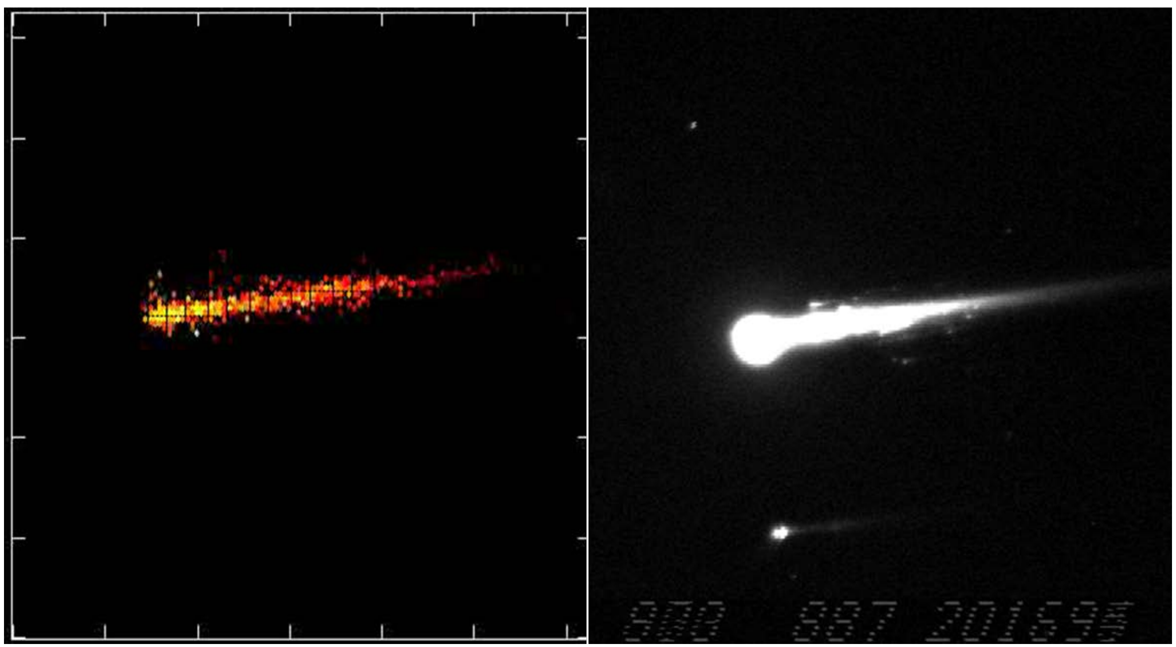
Post re-entry analysis: Learning from observations

- For larger and heavier spacecraft the chance exists that their interaction with the atmosphere is observed and/or parts are retrieved.
    - A few hundred of re-entry events have been reported and correlated with events
    - Less than a hundred re-entry events have occurred where debris pieces were at least tentatively identified as belonging to a spacecraft (the majority pressure vessels).

- As independent validation tool for break-up simulation software, observations of sightings can be forward modeled:
    - Observation model for heating from the break-up event.
    - Camera and filters can be model.

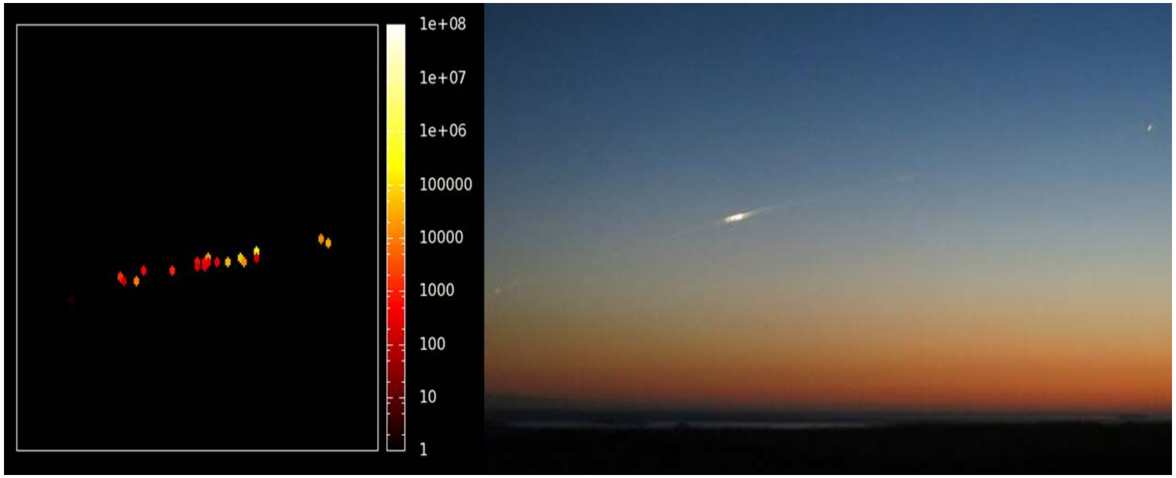
Post re-entry analysis: Learning from observations

- Observations of the explosive break-up of ATV-1
  - ESA's ESESAM code used as break-up simulation software,
  - Observer is an airborne campaign.

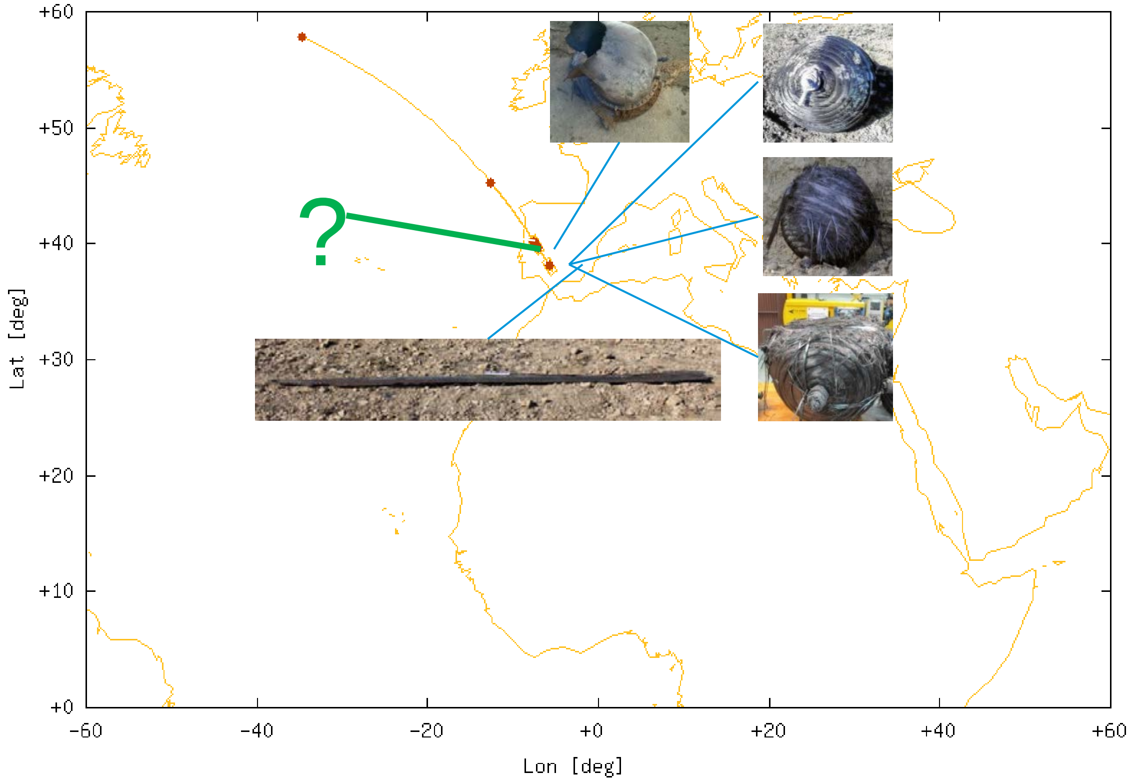


Post re-entry analysis: Learning from observations

- Observations of the thermal-mechanical break-up of GOCE
    - ESA's Scarab code used as break-up simulation software,
    - Observer is a lucky person on the Falkland islands.

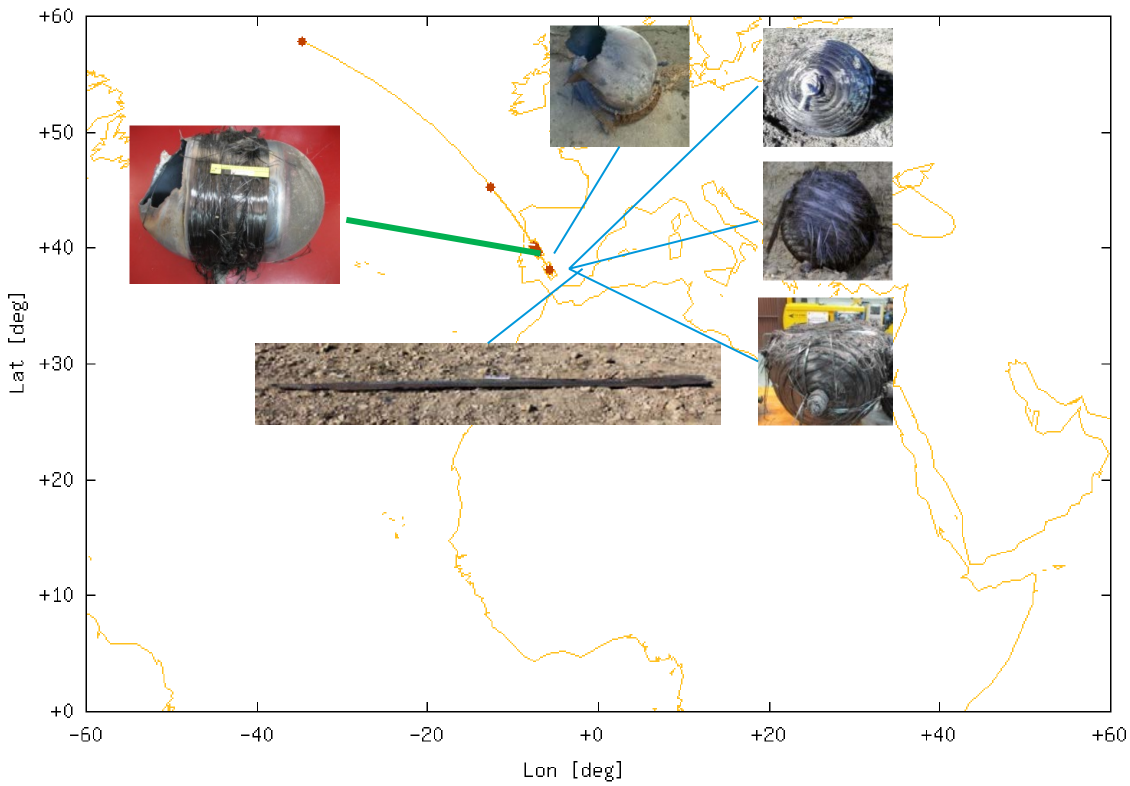


Post re-entry analysis: Fragment identification



- Re-entry event observed over Spain on 2016-11-03 at 6UTC.
- Five piece found between the 3rd and 16th of Nov. 2015 were tentatively attributed to the event
- The ground track can help to identified the source object
- Object oriented break-up code helps to understand the event and postulated three more large pieces.

Post re-entry analysis: Fragment identification



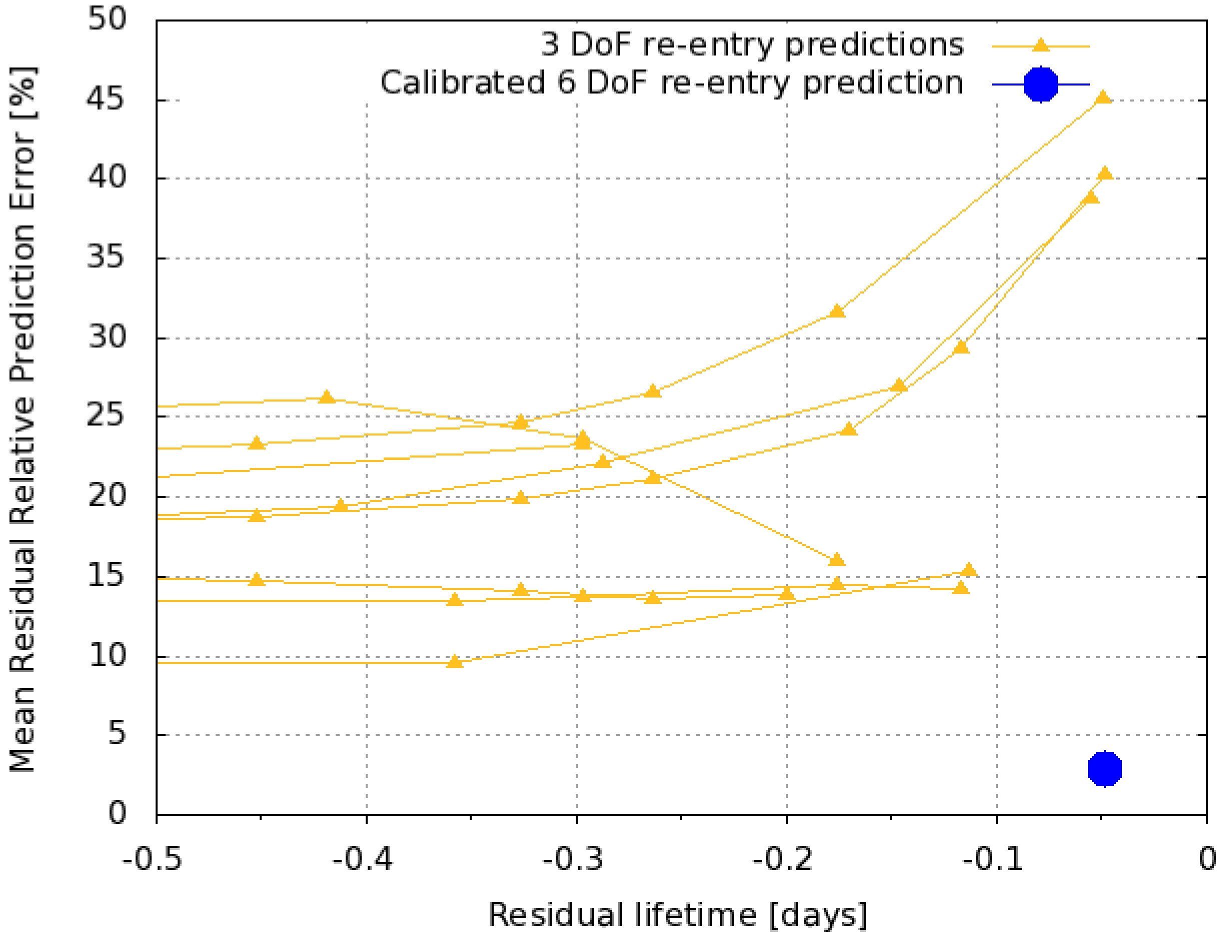
- Re-entry event observed over Spain on 2016-11-03 at 6UTC.
- Five piece found between the 3rd and 16th of Nov. 2015 were tentatively attributed to the event
- A six piece (pressure tank) was found within reasonable limits of the prediction based on it physical properties on

  2016-03-08

Re-entry Prediction Service: Conclusion

- Automated re-entry prediction near the epoch of re-entry can reach state-of-the-art quality in terms of E_P.
- This level of accuracy is required for the use of the data by civil protection agencies or to facility observations, but only for large objects.
- The service is available for registered users since 1999.
- ESA's service processes 170000 objects in under 10 hours daily on a single core, so there is room for improvements:
  - Pre-filtering of orbital states to aid the shooting method,
  - 3 DoF versus 6DoF analysis for objects with a low *B* parameter,
  - Continued modelling of break-up events.

Back-up



3 DoF re-entry predictions
Calibrated 6 DoF re-entry prediction
Mean Residual Relative Prediction Error [%]
Residual lifetime [days]
50
45
40
35
30
25
20
15
10
5
0
-0.5
-0.4
-0.3
-0.2
-0.1
0