NOTES with https://reentry.langbroek.org

Accurate reentry forecasting is a challenge. Various factors influence the accuracy in a negative way. There are often 'unknowns' involved for which guestimates have to be made, and the actual state of the atmosphere varies over very short timescales and spatial scales beyond the generalistation of the model atmosphere used.

1. REENTRY FORECAST ACCURACY, AND FACTORS INVOLVED

Reliable values for the mass and size of objects are often lacking: here *guestimates* have to be made. The main resources used for dimensional and mass information are ESA's DISCOS database and Jonathan McDowell's Space Catalogue: but the two are frequently not in agreement.

Mass values are also uncertain because objects might still contain some remnant fuel adding to the mass, and rocket stages may carry payload adapters of varying mass, or have shed parts during the launch process.

The drag area is often uncertain: apart from often uncertain object dimensions, the drag surface can be (significantly) less than the maximum surface, depending on object attitude. The latter can actually vary over time, e.g. because of tumbling, or because the object self-orients along a preferred axis at some point, or because the satellite operators adjust the object attitude (semi-controlled reentry). At low orbital altitudes, appendages can sometimes separate from the object, changing the drag characteristics.

Our model uses a *default drag coefficient Cd of 2.2*, while in reality, the true drag coefficient of an object can be different depending on shape, size and orbital altitude.

Our Tudat model uses the *NLRMSISE00 model atmosphere*, with observed past, current, and estimated future *Space Weather*. The latter (estimated future Space Weather) is an important factor introducing uncertainty. Space Weather is notoriously difficult to predict, and one solar outburst causing a geomagnetic storm can notably alter the orbital evolution of an object. As the NRLMSISE00 atmosphere strictly speaking needs 40 days of Space Weather *after* the date of interest in order to model the *current* state of the atmosphere, there *always* will be model uncertainty when forecasting, even over short timespans of a few hours.

As a result, even when running the model with the *very same* drag area and mass parameters, and the *same* starting orbit, but with an update of the Space Weather and future Space Weather forecast inbetween the two runs, differences of up to 10-15 minutes in the modelled reentry time can be introduced solely by changes in the Space Weather forecast; even when the two Space Weather updates and model runs are performed on the same day (!).

We try to tune the model by adjusting the drag surface to the observed evolution of the orbital altitude for the object over the previous few days to weeks. This drag surface estimate is daily revised, to account for differences between forecast and real Space Weather, as well as for true variations in drag surface due to attitude variations.

Uncertainties quoted with the Tudat forecasts are based on a standard 20% of the time between the forecast result and the epoch of the orbit on which the forecast is based (see for example Pardini et al 2006).

2. REENTRY DEFINITIONS

This is *not* a trivial point, and should be taken into account when interpreting and comparing reentry estimates by various organisations, and in matching predictions to actual sightings or on-the-ground space debris encounters.

Reentries are not instantanious. They are a *prolonged* process, with a duration of several minutes, and take place along a long (1000+ km) geographical trajectory, and a significant stretch of atmospheric altitudes.

So what do, for our Tudat forecasts and those of several other organisations, the times and locations actually refer to?

In our *Tudat* model, we generally run the simulation to an end altitude of *50 km*. At that altitude, much of the initial mass has already ablated, profound fragmentation has occurred, and any remaining fragments have lost most of their forward momentum, starting a vertical free fall (taking several minutes to even many tens of minutes to reach Earth surface, depending on the area-to-mass ratio of any remaining fragments).

By comparison, the *pre-reentry US CSpOC TIP's* at Space-Track are for an altitude of *10 km*. Their *post-reentry TIP's* (those published after the reentry and quoted with a +- 1 minute precision) on the other hand are, as Jonathan McDowell and I strongly believe (and circumstantial evidence supports that belief), NOT based on a reentry model, but actual Space-based observations of the start of the reentry fireball as registered by US DoD early warning satellites (DSP, SBIRS). As such, they refer to altitudes of *~90-80 km*.

The European *EU-SST* reentry estimates refer to an altitude of *80 km*.

So, to recapitulate, reference altitudes (and positions) are for:

- **Tudat**: 50 km
- **US CSpOC TIP**: *pre*: 10 km;
  post (+- 1 min precision): ~90-80 km
- **EU-SST**: 80 km

EXPLANATION OF SYMBOLS IN THE WEBSITE TABLES

* = latest forecast
X = erroneous forecast, ignore
R = recast of previous forecast
A = aftercast (usually performed 1-2 days after the reentry to account for real Space Weather)

Dr Marco Langbroek
Delft University of Technology
Faculty of Aerospace Engineering

document written 10 November 2025 - revised 21 November 2025