A Multiscale Heating Correction Code for Space Debris Demise Simulations

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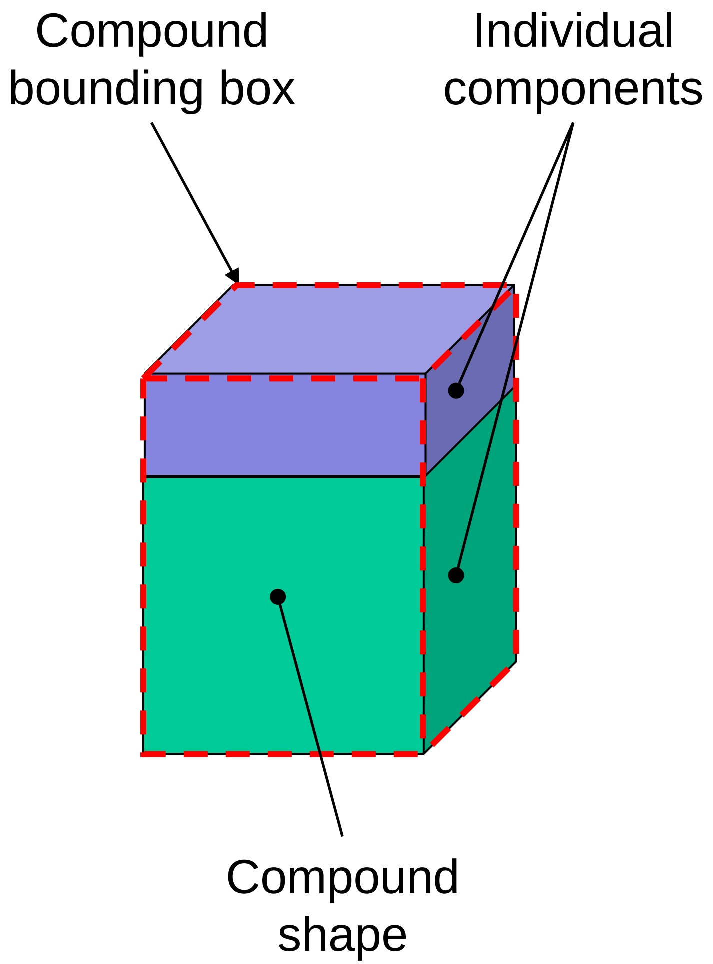
CRITIC overview

- The CRITIC software is designed as a wrapper for re-entry simulations run using the ESA DRAMA suite.
- CRITIC implements local length scale corrections to aerothermal calculations output by DRAMA's SESAM (Spacecraft Entry Survival Analysis Module) re-entry simulator.
- CRITIC has been employed in this de-risk activity to generate database files that can be read by the FNC prototype software.

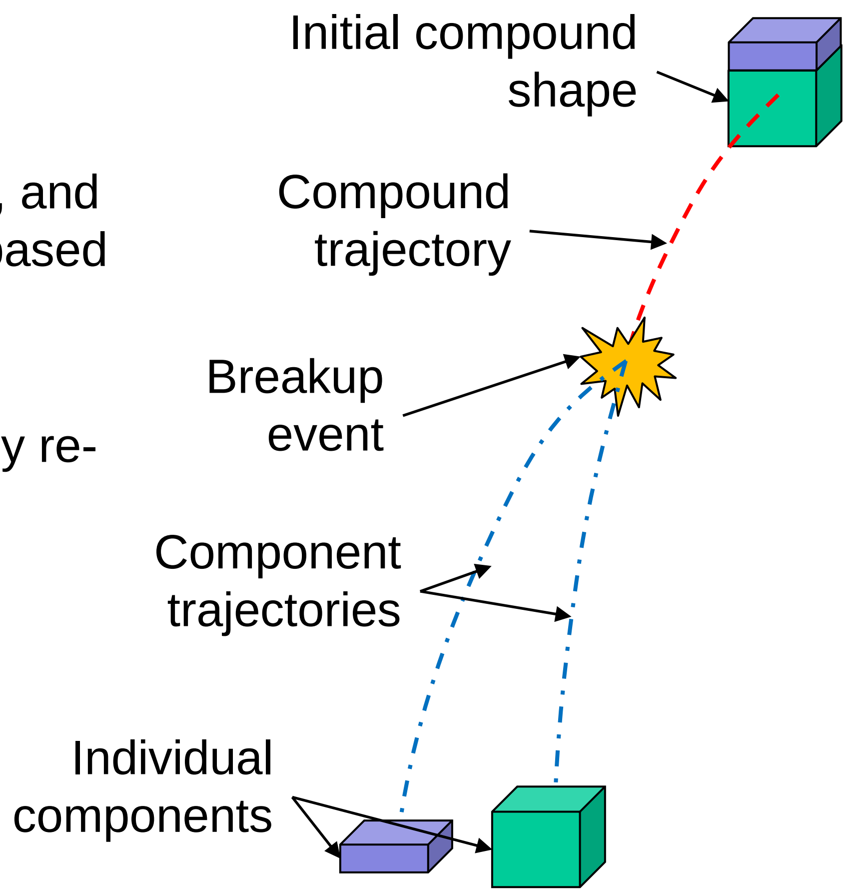
CRITIC overview

- Thermal scaling factors are tabulated using $\ln\left(\frac{length}{width}\right)$ and $\ln\left(\frac{length}{height}\right)$
- These factors are interpolated based on each component or compound shape's bounding box.
- Component scaling factors relative to their parent compound shapes are also calculated.
- The factors are then applied to the aerothermal heating of SESAM simulations.



CRITIC overview

- CRITIC initially runs a single SESAM simulation.
- Breakup and impact events are logged, and thermal scaling factors are calculated based upon resulting fragment sizes.
- SESAM simulations are then recursively re-run using successive breakup/impact/demise conditions as inputs.
- This process is repeated until all components have either demised or impacted.

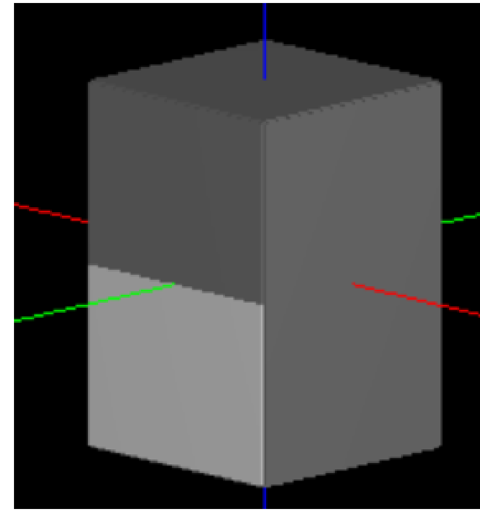


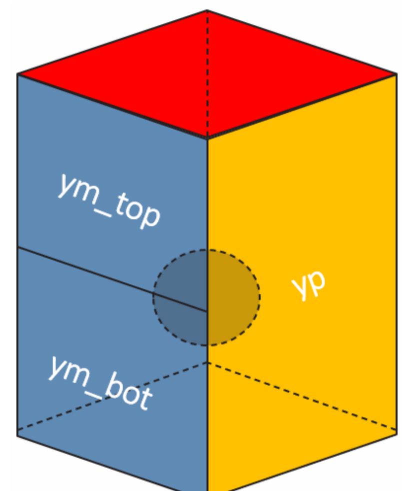
Verification and testing

- CRITIC simulations have been performed both with and without scaling enabled.
  - This facilitates verification that thermal factors are being calculated and applied correctly.
  - Local length scale corrections to component heating should be demonstrated by lower heating to smaller sub-components.
  - As such, the scaled sub-panels in subsequent test cases should demonstrate *lower heating* with CRITIC scaling enabled.

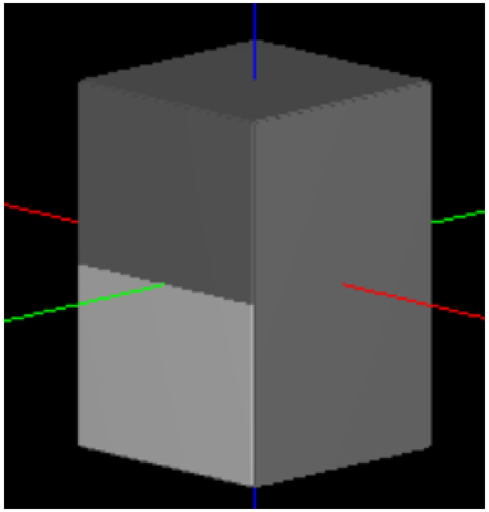
Initial test cases

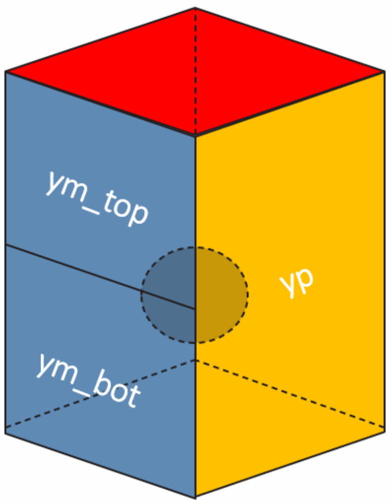
- The first test case evaluated represents a cuboidal satellite analogue.
- An undemisable variant of Al-7075 is applied so that all components survive until ground impact.
- The analogue comprises:
  - A central ballistic sphere
  - 3 rectangular lateral panels
  - 2 square top/bottom panels
  - A lateral panel split into two halves at its centreline (always attached to one another in present examples)





Initial test cases



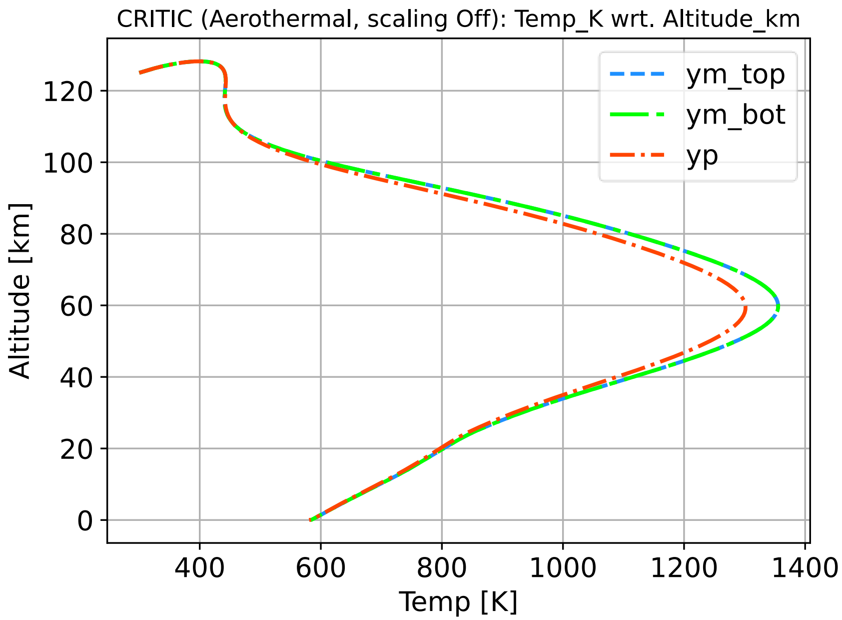


- The following scenarios have been evaluated using the halved compound panel:
  - <u>No breakup</u>

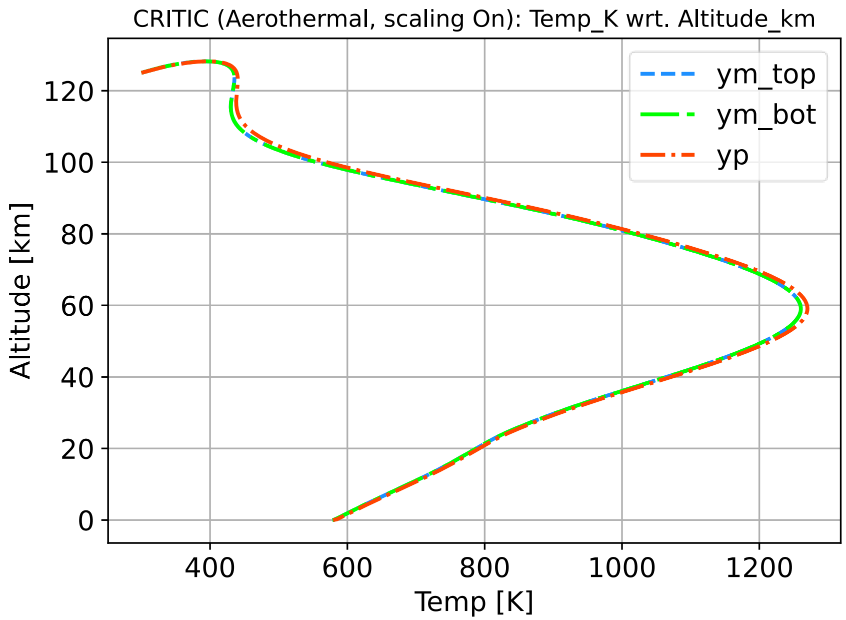
    No breakup occurs and all components remain attached to one another throughout the re-entry trajectory.
  - <u>Set temperature breakup</u>

    Components of interest separate from the main object when they reach a predetermined temperature (1000 K).

Initial test case - results



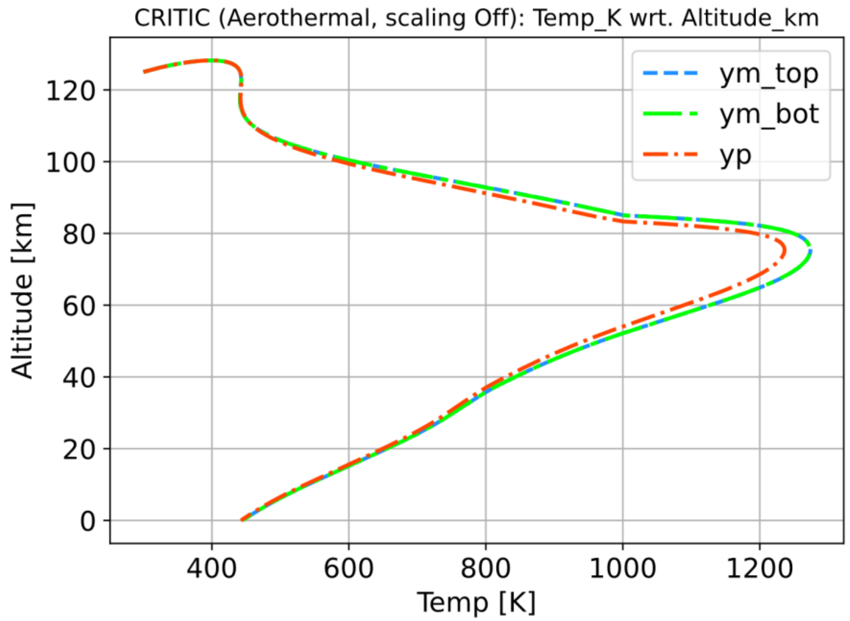
CRITIC scaling off



CRITIC scaling on

- Results of scaled “no breakup” simulations performed using un-demisable component joints.
- Reduced thermal transport to the sub-panels (ym_bot, ym_top) is evident compared to the full-size panels (yp).

Initial test case - results



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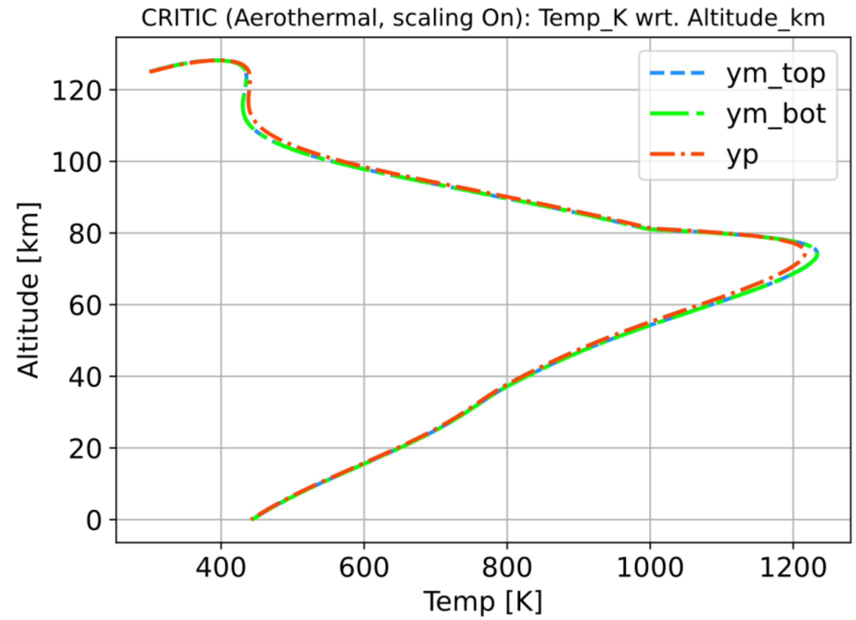
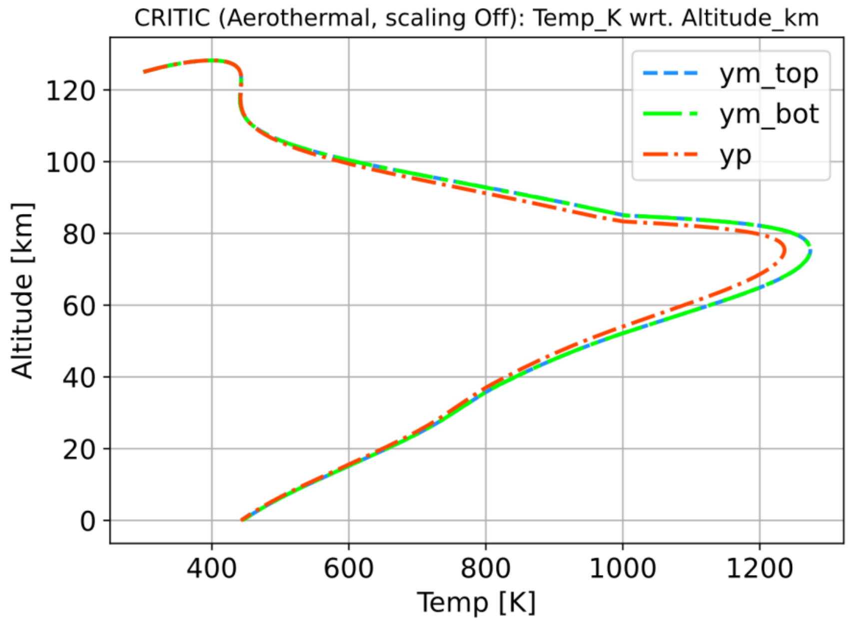


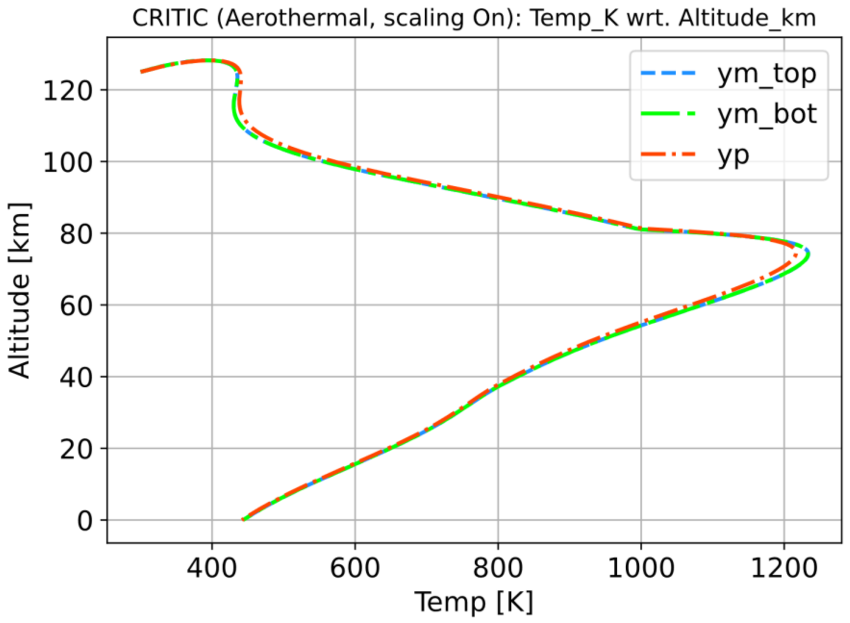
CRITIC scaling on

- Results of the "set temperature breakup" simulations performed using a child release temperature of 1000 K are shown.
- With CRITIC scaling, the smaller panels (ym_bot, ym_top) reach their release temperature at a lower altitude than without, indicating the expected behaviour.

Initial test case - results



CRITIC scaling off



CRITIC scaling on

- The unitary panel (yp) also receives slightly lower heating with CRITIC on.
- This is because the parent object heating is slightly lower than the shaded individual panel heating (~10% lower).

Revised test cases

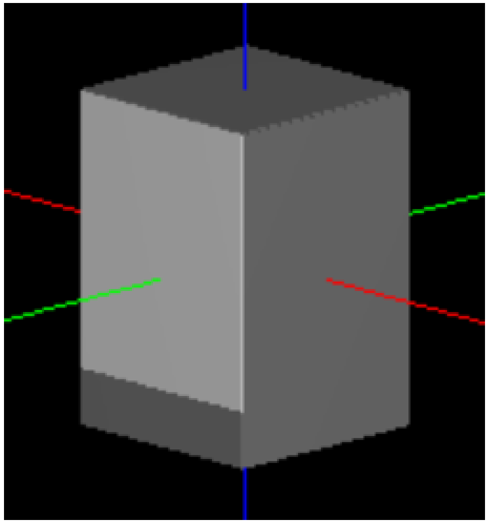
- A revised test case was defined based featuring an unevenly split lateral panel to better demonstrate the impact of CRITIC corrections.

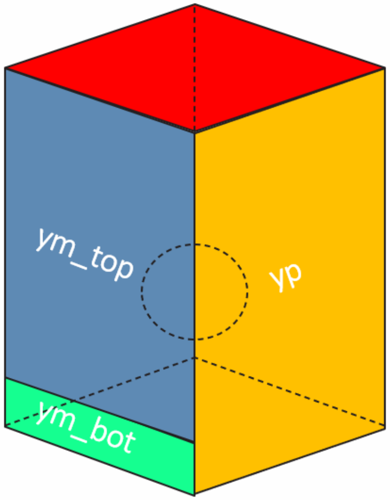
- The other components and structure of the original test case were retained.

- CRITIC is once again shown to produce good agreement for split panels compared to the existing DRAMA heating method.

Revised test cases

- Unevenly split compound panels have been used to extend verification activities.
- The evenly split panel in the previous test case produces the same output for both halves.
- Simulations featuring an uneven split allow scaled heating to be further examined wrt. relative component scales within compound shapes.



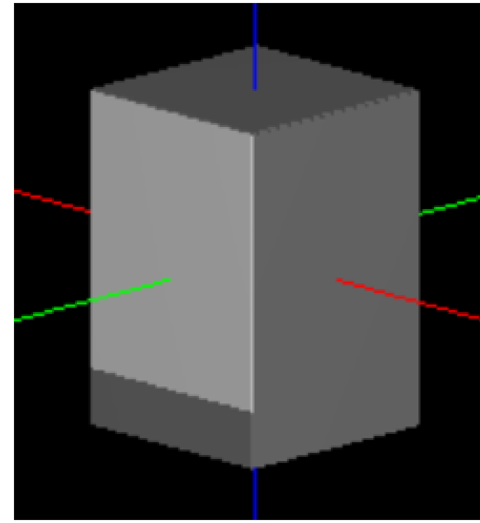


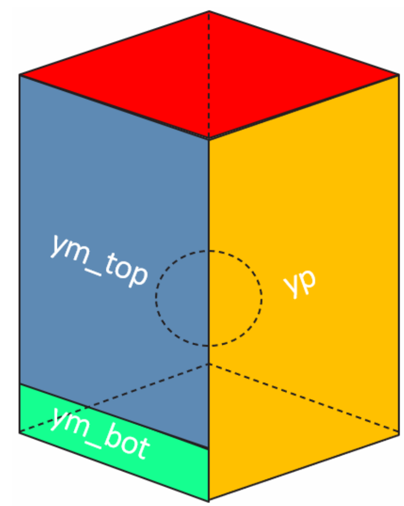
Revised test cases

- The split panel in the revised test case is divided into two sections, one 2.5m high and another 0.5m high.

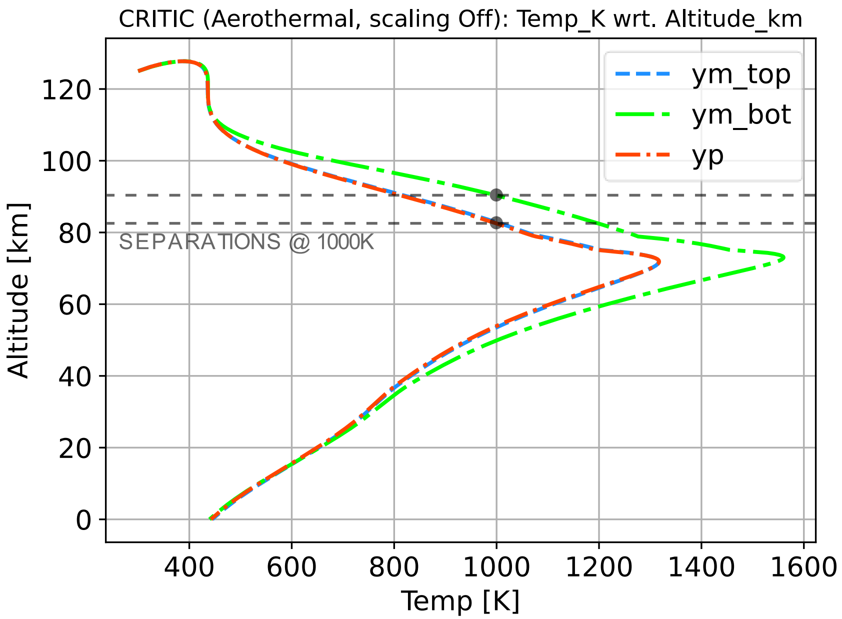
- The separation temperature for the split panel compound was set to 1000K as in previous simulations.

- As such, the panels are unevenly heated and separation from the main object occurs later in the trajectory.

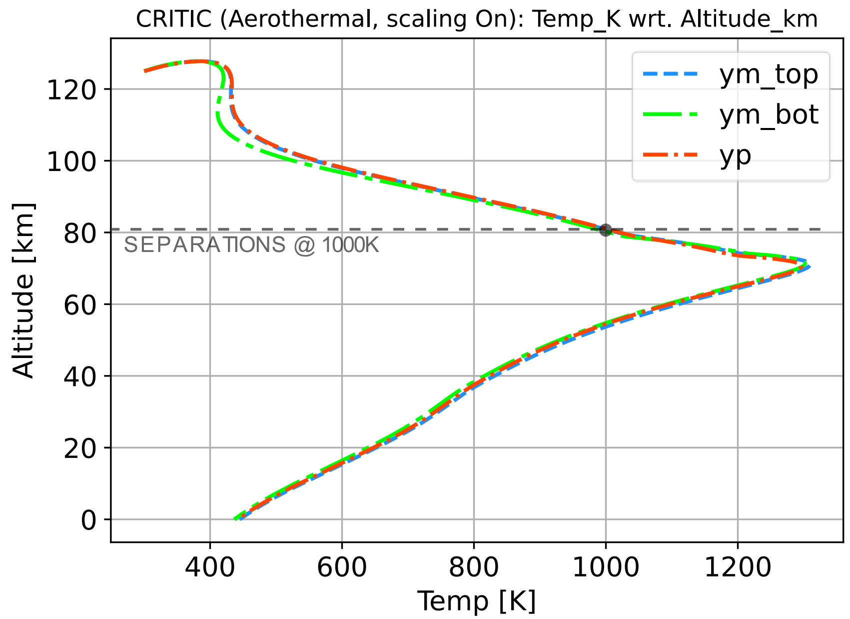




Revised test cases - results



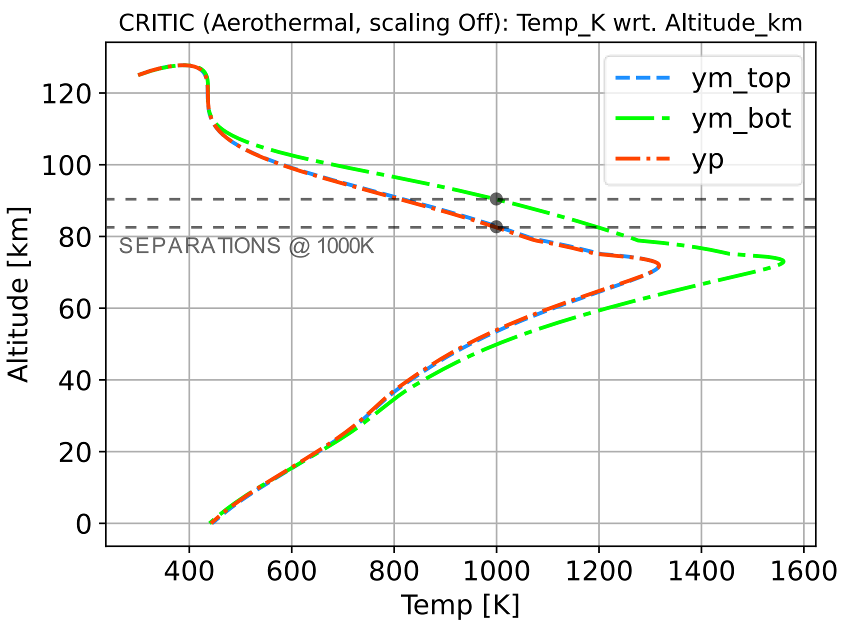
CRITIC scaling off



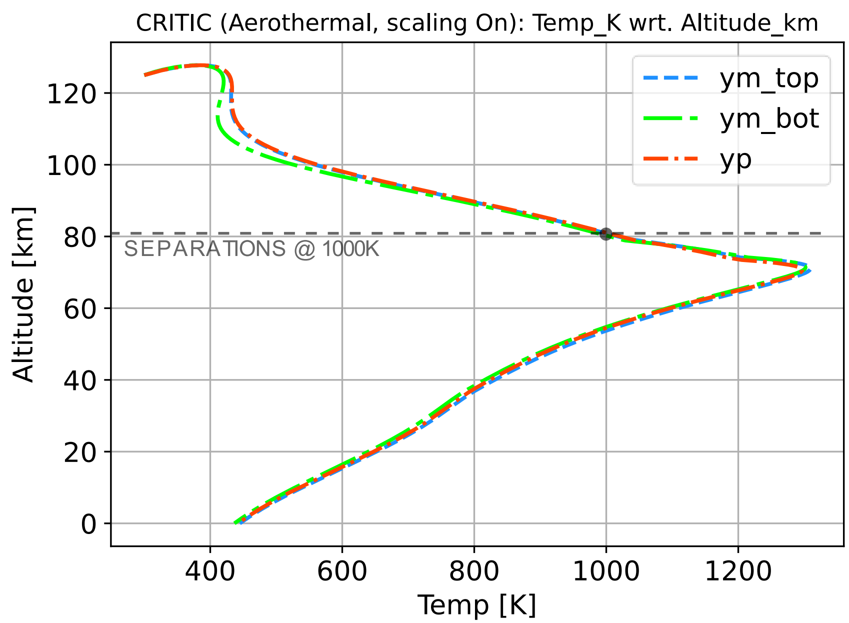
CRITIC scaling on

- Results of "uneven panel" simulations performed using a child release temperature of 1000 K are shown.
- Significant overestimation of heating to the smaller of the two panels (ym_bot) can be seen in the uncorrected results, leading to earlier separation.

Revised test cases - results



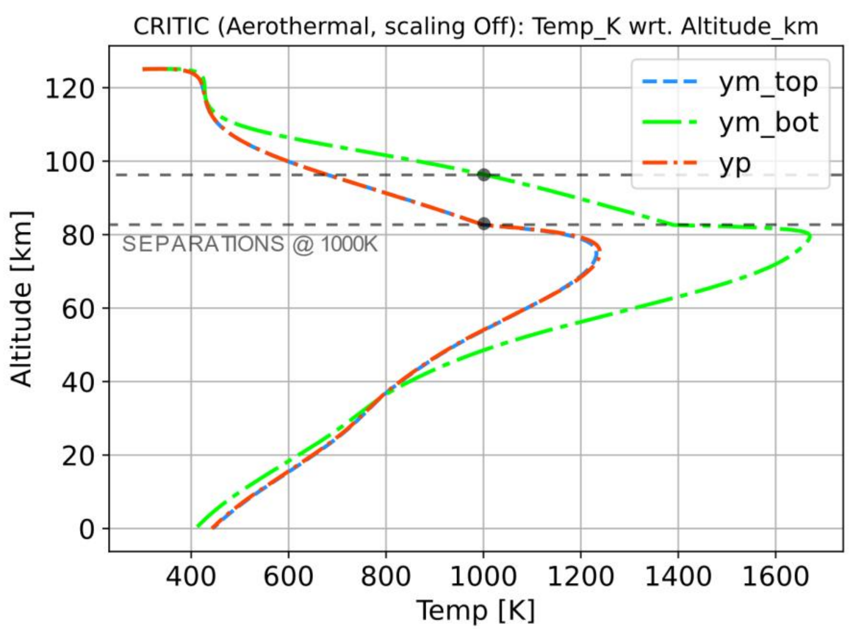
CRITIC scaling off



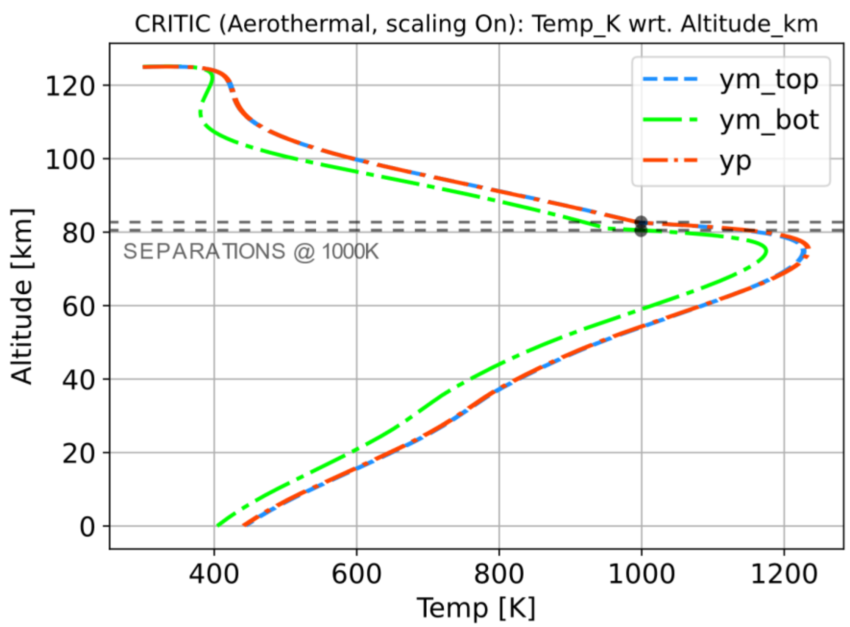
CRITIC scaling on

- With CRITIC scaling, the temperatures of both split panels (ym_bot, ym_top) agree well throughout their trajectories.

Revised test cases - results



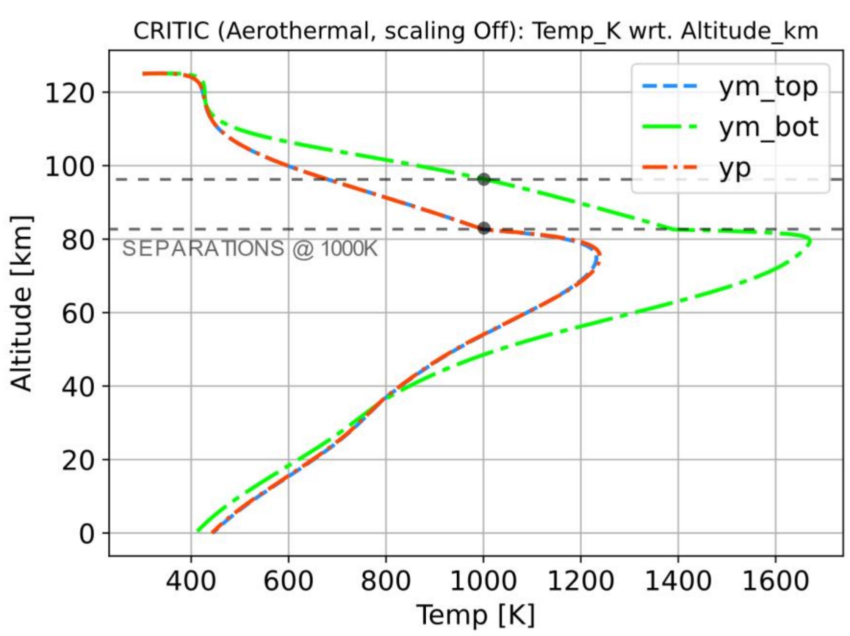
CRITIC scaling off



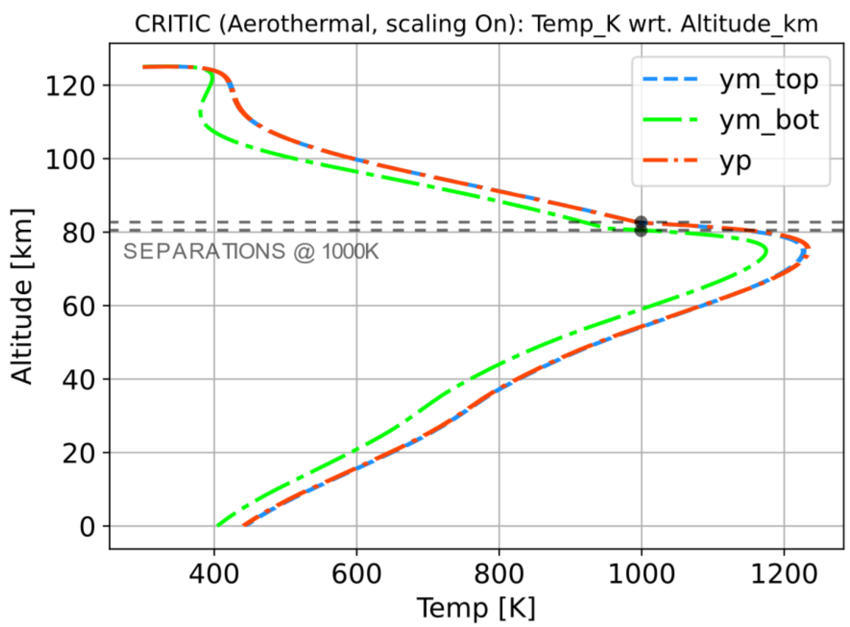
CRITIC scaling on

- Results of a second set of "uneven panel" simulations wherein the small panel was further reduced in size to 1/30th that of the full panel are shown.
- Once again, significant overestimation of heating to the smaller of the two panels (ym_bot) is present in uncorrected results, leading to earlier separation.

Revised test cases - results



CRITIC scaling off



CRITIC scaling on

- With CRITIC scaling, the temperatures of both split panels (ym_bot, ym_top) agree reasonably well throughout their trajectories.
- The discrepancy in temperature history in this case is due to the limited resolution of SESAM’s shading algorithm and the (extremely) small proportions of the ym_bot panel.

Conclusions

- The heating predictions generated by SESAM become less accurate as the detail of the spacecraft model in increased.

- CRITIC compensates for these overestimations in box primitives by correcting the heating via a scaling factor.

- Excellent agreement in temperature history is obtained between panels of various sizes when CRITIC scaling is applied.

Conclusions

- These length scale modifications mitigate a potential pitfall with the present component-based approach of DRAMA, namely:
  - Greater detail in compound shapes leads to higher heating.
  - The danger is that users associate a higher level of detail with less conservative analysis
  - In actual fact, more detail can lead to lower accuracy.
  - The results shown here should motivate future updates to mitigate this potential pitfall.

Conclusions

- In compound shapes whose components are of approximately equal size, the heating error is around 20-30%
  - This is in line with the heating uncertainties applied in the recent PADRE activity (Probabilistic Assessment of Destructive ReEntry).
  - This applied uncertainty was one of – if not the most – significant aspect with respect to the statistical spread of output metrics (such as casualty risk).
  - This demonstrates the importance of removing this systematic inaccuracy.
  - The problem is more extreme for lager separations in length scale.

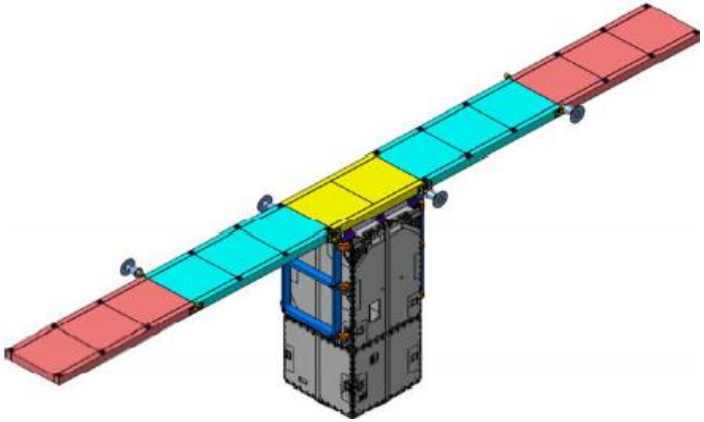
Conclusions

- The present method employed in CRITIC involves significant human input to identify cases where length scale adjustment is necessary.
  - The automation of this process will require significant thought in terms of the identification of shape recognition algorithms.
  - The appropriate scaling is not known for all compound shapes.
  - We have restricted ourselves to boxes for study tractability.
  - There is a great deal more work to do in order for this method to be generally applicable.

Future work

- In the near future, we intend to further demonstrate the utility of CRITIC by extending the simulations presented here
- The code will be used to analyse the heating of SAR arrays on spacecraft in LEO such as those mounted on the Sentinel-1 or Harmony spacecraft
- The current capabilities of CRITIC lend themselves well to analysing the thermal environment experienced by the various cuboidal structures typical of SAR arrays
- These have previously been sources of significant uncertainty in re-entry and demise simulations

https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-1/Mission_ends_for_Copernicus_Sentinel-1B_satellite



https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-1-sar/sar-instrument/description

Thank you

Questions?