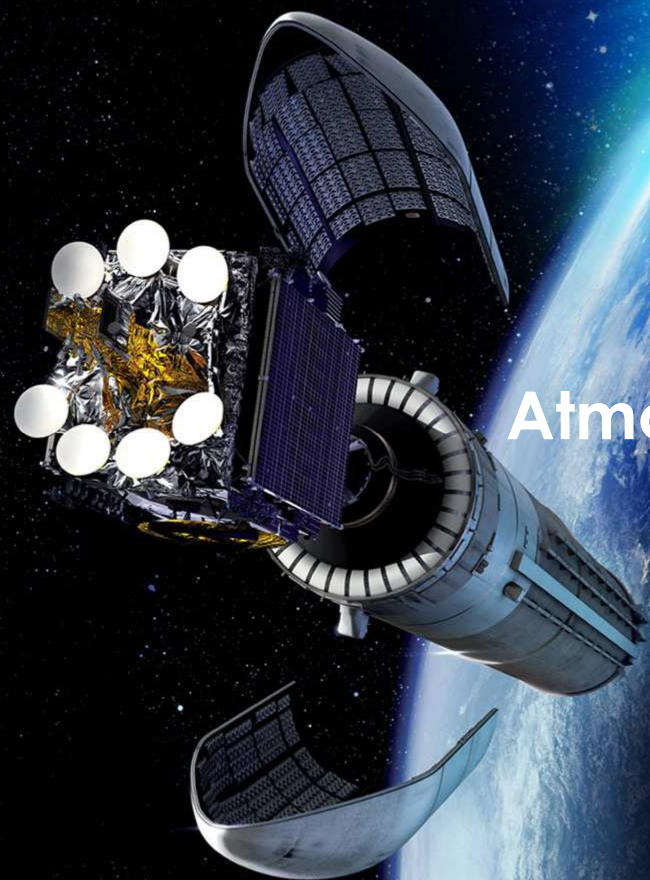

Atmospheric Re-entry Assessment ARA

CleanSat Industrial Days

ESTEC October 24-26 2017

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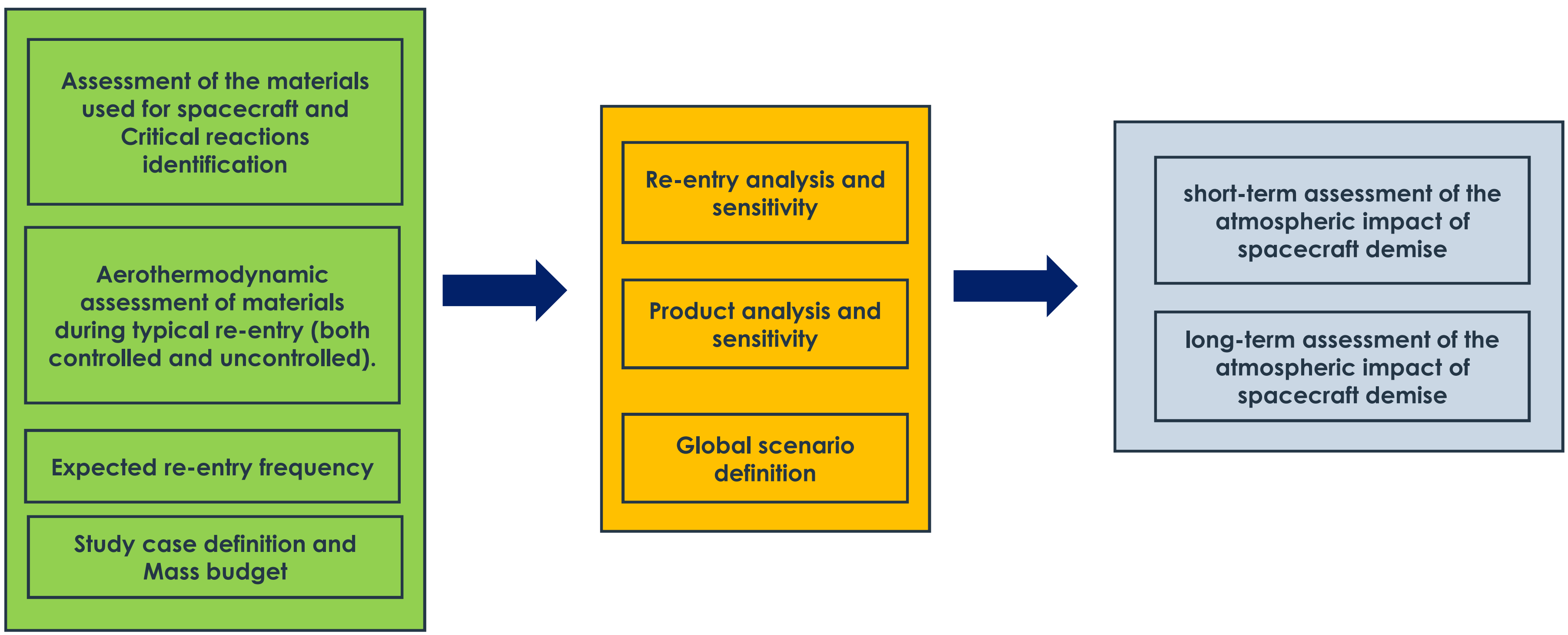
ARA - Atmospheric Re-entry Assessment

Objective of the study:

Investigate of the potential impacts on the atmosphere and on climate, caused by gases and particles released during the re-entry of spacecraft and rocket upper stages.

ARA study overview



Assessment of the materials used for spacecraft

Main materials and reactions typology

- Metallic materials
  - Aluminum alloys
  - Titanium alloys
  - Stainless Steels
  - Inconel
  - Nextel

→

- Oxidation
- Melting/Sublimation
- Ablation / Vaporization

- Polymers
  - MLI major structural components
  - Carbon Fiber Reinforced Polymers (CFRP)
  - Etc…

→

- Oxidation/combustion
- Thermal degradation
- Depolymerization

Main Reactions Identifications

Metallic materials

Metallic materials are the predominant ones:

- During the re-entering the metal parts will experience increasing temperature, pressure and concentration of O_2.
- **Oxidatio**n will be the principal phenomenon together with **ablation /vaporization/ sublimation and melting**.
- Growing concentration of oxidized metal particles can **catalyze other reaction involving atmospheric Nitrogen and Oxygen** leading to global depletion of these species and increase the total amount of particles present in the atmosphere.

Main Reactions Identifications

Non-metallic materials

- As metallic parts, the non-metallic ones during the re-entering will experience increasing temperature, pressure and concentration of O_2.
- However reactions in which polymers are involved are more complex.
- Polymers could undergo **depolymerization** or **thermal degradation**. Those reaction will lead to **formation of gaseous monomers** and **byproducts that in presence of Oxygen or Ozone could combust** generating **CO, CO_2, NOx and H_2O.**
- General reaction is $CnHmOxNyFz + O_2 \rightarrow CO + CO_2 + H_2O + NO + NO_2 + N_2O_5 + HF$
- Thermal degradation **products** are generally **gaseous species** plus **carbonized residue** which can increase the particulate present in the atmosphere.

Atmospheric impact

- Atmospheric Ozone is produced and consumed by different reaction involving oxygen, it's radical and NO.

- The **equilibrium** is maintained **if** those **products** or **reagents are not consumed to form other species.**

- Reactions produced from a reentering debris can interfere with the Ozone production by:
  - Directly consume O_2, O_3
  - Produce NO, CO_2, CO H_2O
  - Produce radicals which can react with O• , O_3, O_2, NO

Atmospheric impact

Spacecraft re-entering from space could interfere with environment

List of critical substances to ozone layer destruction

- - NO_y: NO, NO_2, NO_3, $BrNO_2$, $ClNO_2$, HNO_4, HONO, PAN, N_2O_5, HNO, HNO_3, $ClNO_3$
- - HO_x: H, OH, HO_2
- - Cl_y: Cl, Cl_2, ClO, OClO, Cl_2O_2, OClO, $ClNO_2$, BrCl, HOCl, $ClNO_3$, HCl
- - Br_y: Br, Br_2, BrO, HOBr, HBr, $BrNO_2$, $BrNO_3$
- - Source gas for Cl_y, Br_y: chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC)
- - Source gas for NO_y: N_2O

Why they are critical

- - (NO_y) those components produce NO by ultraviolet, which helps the O_3 to become O_2.
- - (HO_x) HO_x produce OH, which helps the O_3 to become O_2.
- - (Cl_y) those components produce chlorine Cl (photodissociation), which helps the O_3 to become O_2.
- - (Br_y) In the stratosphere, ozone layer can be destructed by chemical reactions including Br_y. This can help O_3 to became O_2.

Identification of critical altitude ranges for the release of anthropogenic substances

Assessment of the altitudes at which they are critical

- For the first iteration, the simplified assumption is used that the lower altitude becomes more important on the climate impact.
- Atmospheric pressure decreases exponentially with an increase in altitude. 99.9 % of the total amount of air exists in the troposphere and stratosphere (up to 50 km). At 80 km, the pressure decreases by 0.01 hPa: 99.999 % of the total amount of air exists below 80 km. The ECHAM/MESSy atmospheric Chemistry model (EMAC) actually performs a numerical chemistry and climate simulation up to around 80 km in the vertical direction. **Little impact is expected on the atmosphere above 80 km by anthropogenic substances** of spacecraft demise.
- **Lower altitude has a large climate impact, particularly, the ozone layer destruction. The ozone layer mainly ranges between 20 and 30 km.** In these altitude ranges (i.e. in the stratosphere), for example, O3 can decrease with an increase of NOy. If O3 decreases in the altitude over 30 km, greenhouse gas decreases in the upper stratosphere, which results in a decrease in temperature, while solar radiation (ultraviolet) increases in the troposphere, which causes an increase in temperature.
  - high critical (< 30 km),
  - medium (30 – 50 km)
  - low critical (50 – 80 km)

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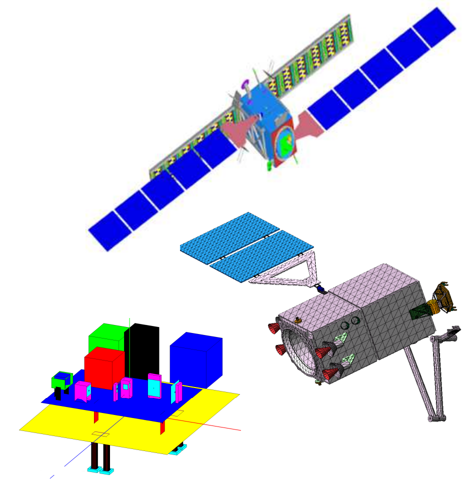
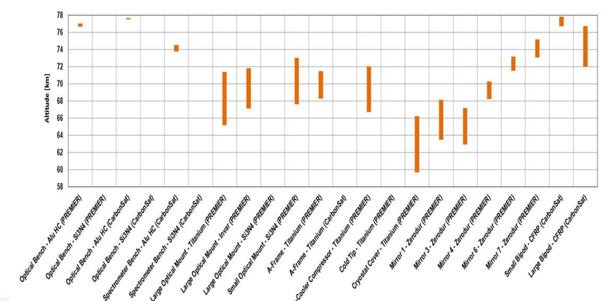
Aerothermodynamic assessment of materials during re-entry

Identification of altitude ranges in which the S/C materials ablate

- To identify the altitude ranges in which the materials on the S/C are ablating (i.e. to altitudes at which there is a continuous release of mass) a large set of simulations was reviewed:
  - data from re-entry dedicated studies and programs (such as D4D, D4OP, Sentinel-1, e.Deorbit, etc.)
  - re-entry simulation on specific S/C, items,

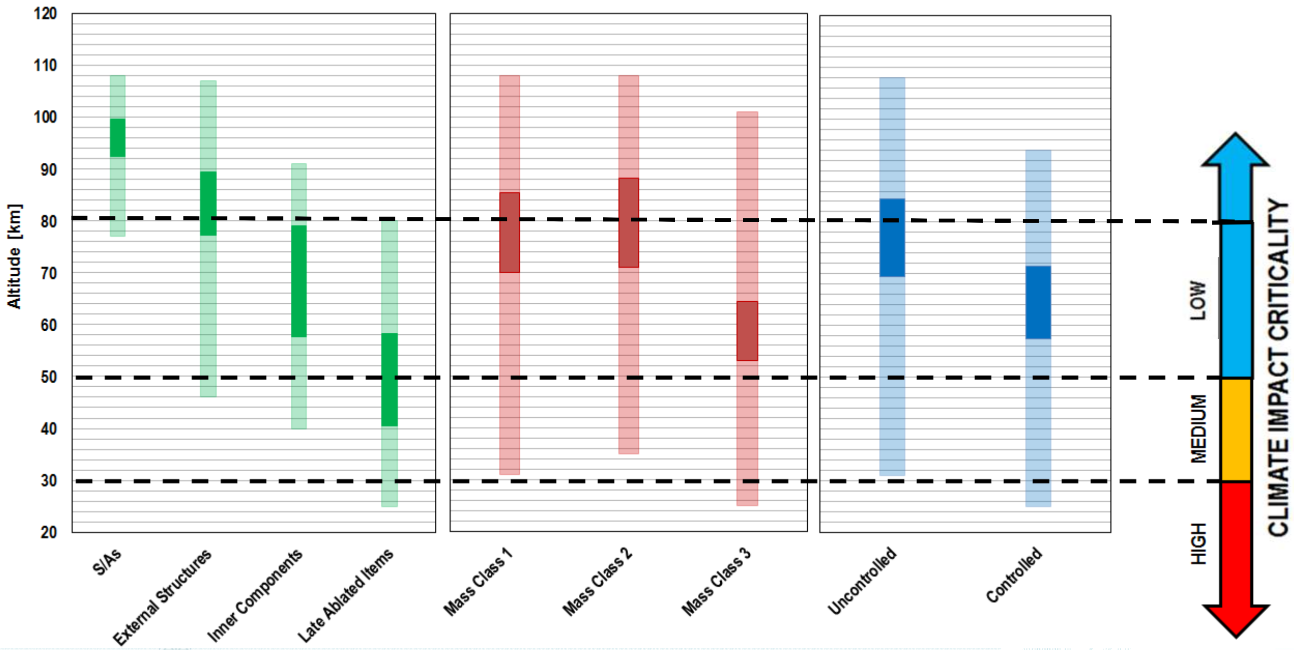
- The available data have been classified according to:
  - satellite mass:
    - Mass class 1: objects up to 1500 kg,
    - Mass class 2: objects from 1500 to 3500 kg,
    - Mass class 3: objects over 3500 kg,
  - S/C different components (S/As, external structures, inner items, etc.) has been considered
  - re-entry typology (controlled and uncontrolled)





Aerothermodynamic assessment of materials during re-entry and critical altitude

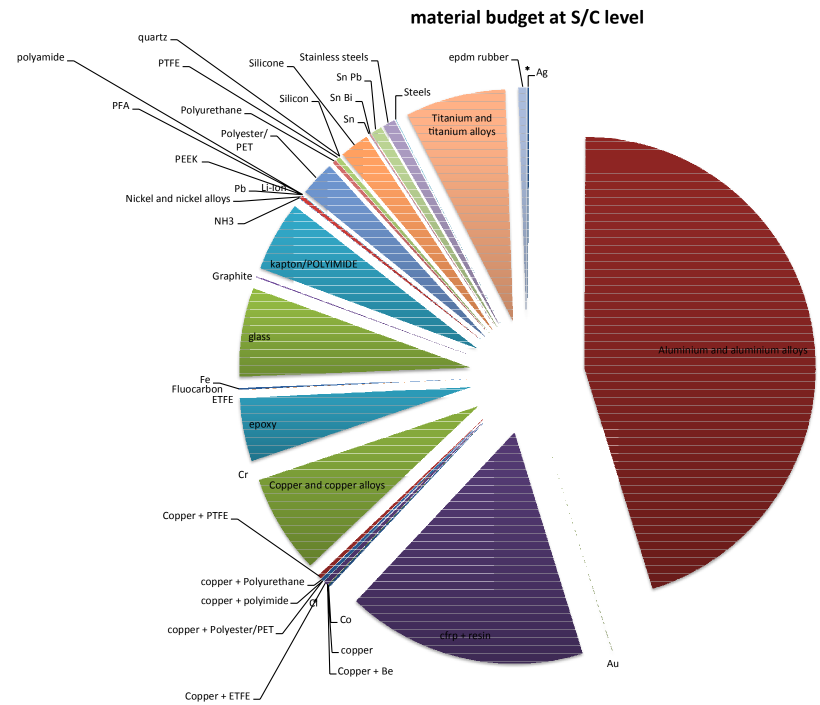
- an identification of the altitude ranges in which spacecraft typically ablate;
- a preliminary identification of the altitude ranges in which a release of anthropogenic substances is most critical.



Re-entry analysis - Model approach

- To properly asses impact on Atmosphere we need to evaluate for each material:
  - Pressure, temperature, ablated mass vs altitude, time, latitude, longitude
- The quantity and the altitude of the released material are related to:
  - Altitude of exposure of the various material → related altitude of exposure of the component (depends on the S/C configuration)
  - Exposed surface
- Need to associate materials to components
  - External→ early exposure
  - Internal→ late exposure
  - →Material budget at component level
- Focus on:
  - late exposure components
  - Material identified in Critical reactions

- → Current state of the art approach to re-entry simulations is not well suited to reach the goal of this study
- Need o to **develop a specific approach to re-entry simulations**

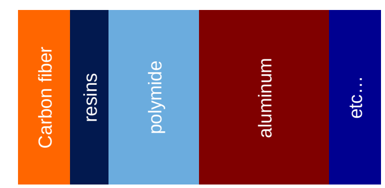


Re-entry analysis - Model approach

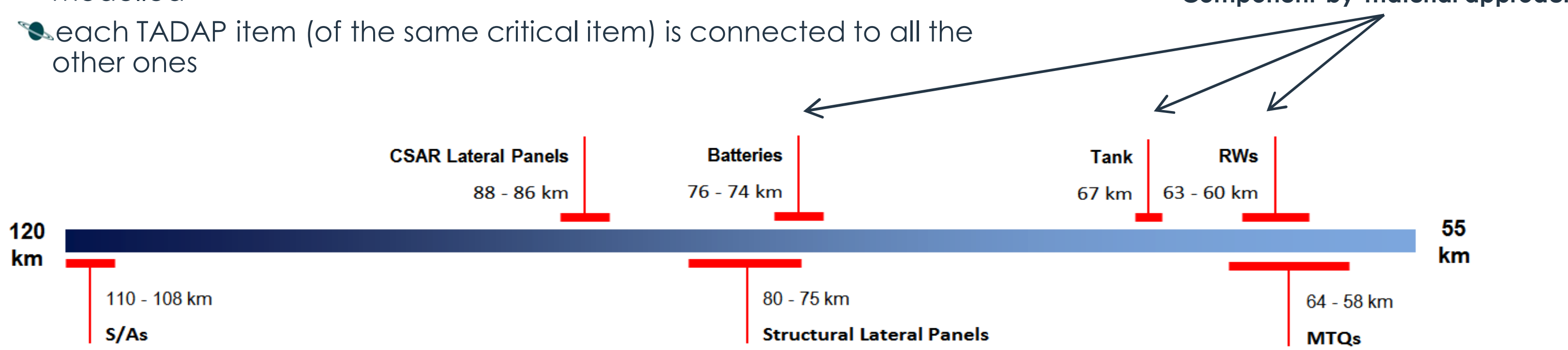
Component-by-material approach

S/C items are modelled in TADAP as:

- a compound of items of the same physical dimensions and same dispositions (overlapped items) but made of different materials
- each TADAP item represents the mass value of a specific material, according to mass budget
- generally 5 different materials (and thus 5 object) are modelled for each S/C item
- at least the most critical materials for atmospheric impact are modelled
- each TADAP item (of the same critical item) is connected to all the other ones



Component-by-material approach



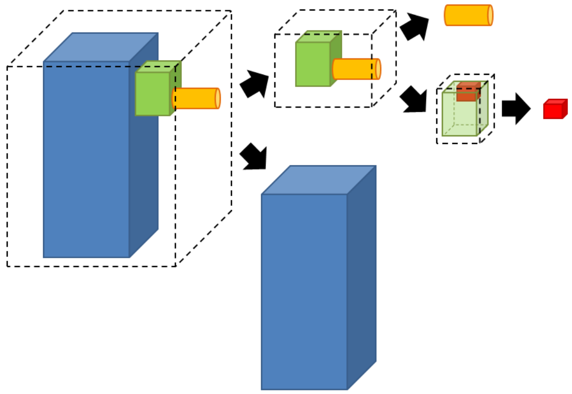
Re-entry analysis tool - TADAP features

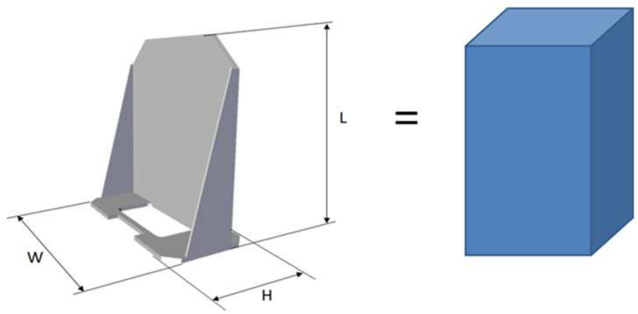
Initial orbit
- Possibility of set up different Trajectory earth fixed initial data

Fragmentation
- Possibility of simulating all the S/C as compound of simple shapes
- Possibility of simulating a progressive fragmentation

Aero-thermal model
- Randomly tumbling heating model - 3DoF model
- Implementation of simplified shielding between the objects (the mutual shielding is updated according to fragmentation process)
- Implementation of thermal conductivity between the objects

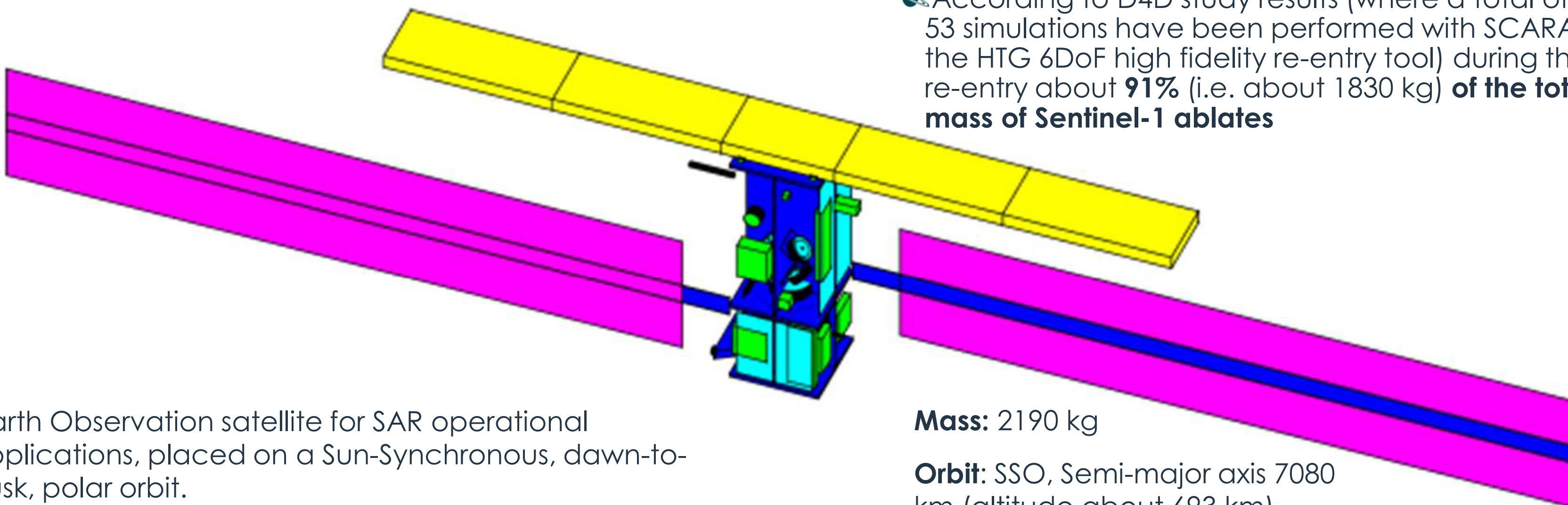
Geometrical
- Adoption of simplified primitives to model complex objects





Re-entry analysis - study case model

- Sentinel-1 is one of the five ESA space missions addressed at supporting the Global Monitoring for Environment and Security (GMES) program.
- Worst case in terms of total mass ablated during the re-entry and thus amount of substances released in the atmosphere.
- According to D4D study results (where a total of 53 simulations have been performed with SCARAB, the HTG 6DoF high fidelity re-entry tool) during the re-entry about **91%** (i.e. about 1830 kg) **of the total mass of Sentinel-1 ablates**



- Earth Observation satellite for SAR operational applications, placed on a Sun-Synchronous, dawn-to-dusk, polar orbit.
- Sentinel-1 C and D will be lunched in the next few years, as part of the Copernicus program Sentinel fleet.

Mass: 2190 kg

Orbit: SSO, Semi-major axis 7080 km (altitude about 693 km), inclination 98.1 degrees

Main feature: large C-SAR

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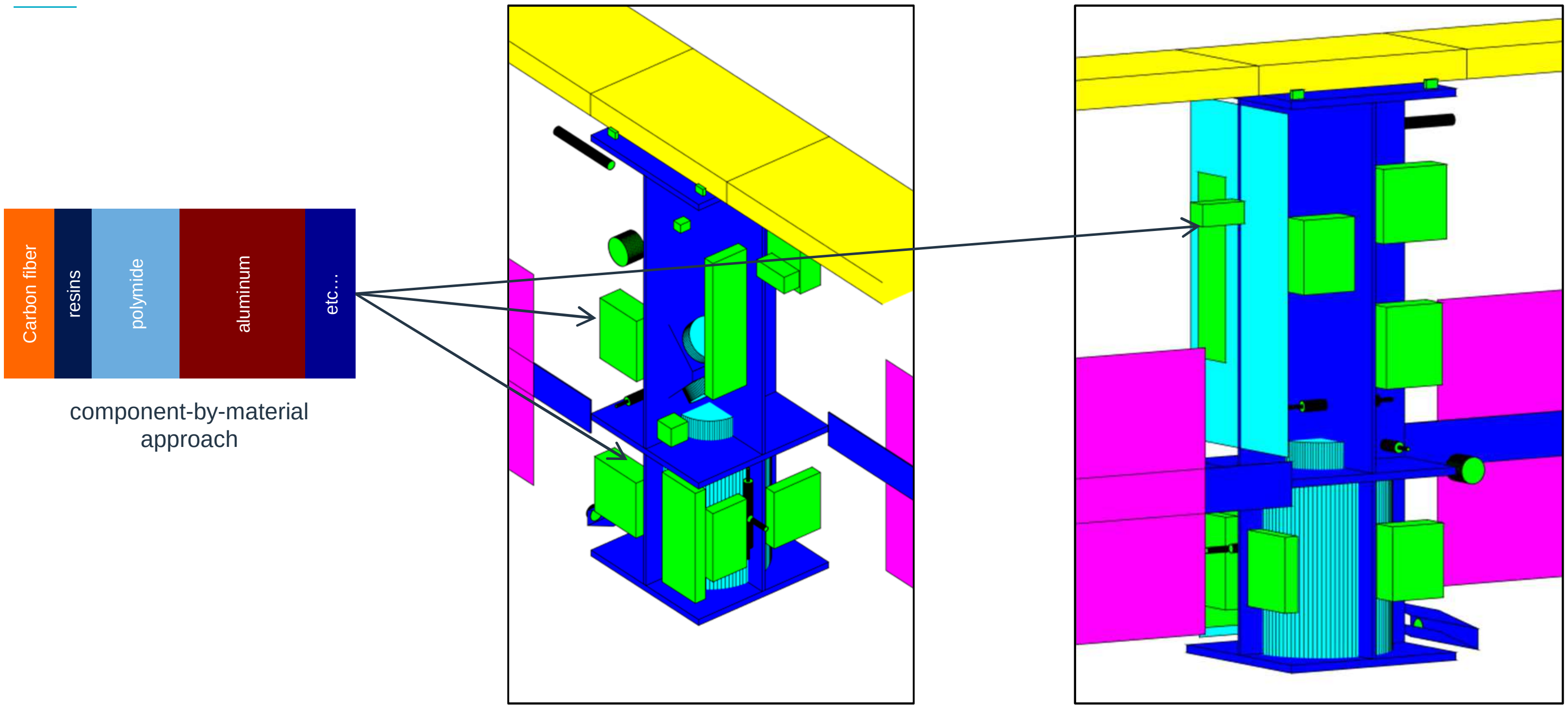
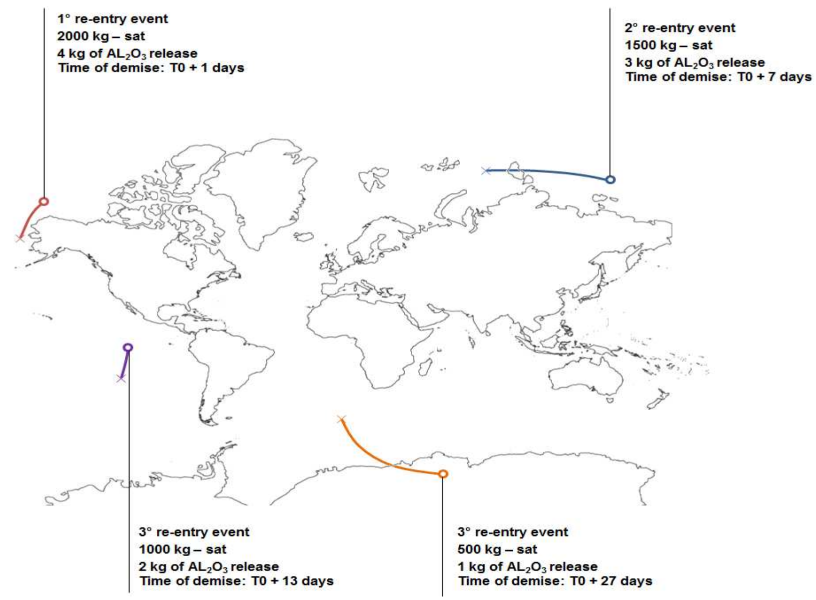
Re-entry analysis - study case model



component-by-material approach

Global re-entry scenario

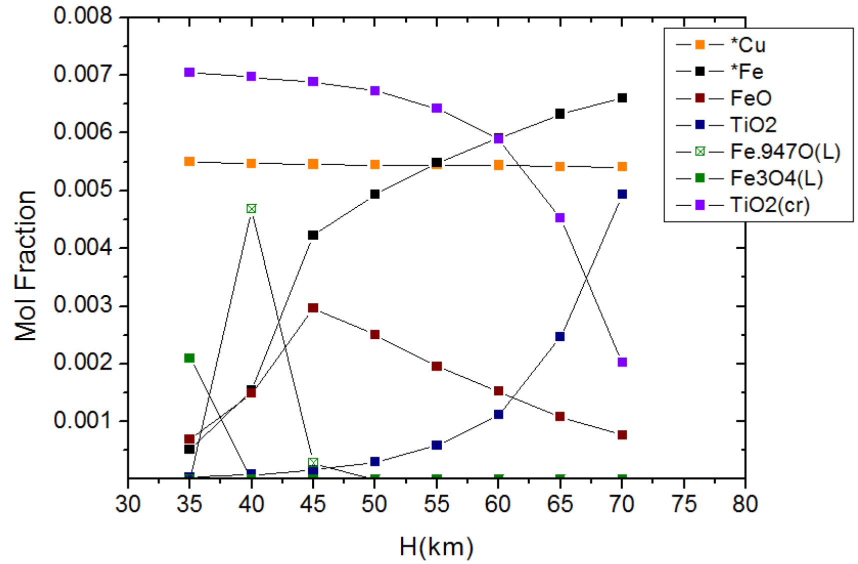
- Assessment of re-entry rate to define the scenario
  - Assess the re-entries rate for the coming decades
  - Assess the main characteristics of future re-entries
- Review the results of re-entry & products analysis for both nominal study case and sensitivity simulations
- Starting from the study case analyses, and re-scaling the simulations results according to the S/C and R/B "re-entry database", define:
  - Global re-entry scenario – realistic
  - Global re-entry scenario - worst case (complete demise)



Product analysis

- Product analysis on the Select Study Case:
  - Detailed re-entry and product analysis
  - Sensitivity analysis

- Inputs:
  - Materials partial masses, products and Trajectory points
- Model:
  - Chemical model (thermo, diffusion-transport, reactions) to evaluate products in the atmosphere per altitude point
- Outputs:
  - relative masses of products per trajectory (altitude) point
  - Products contributing to Ozone depletion concerns + Toxicity



Product analysis outputs example

Product analysis

- The chemistry of metals is clear leading to the most stable oxide; all the thermodynamic properties of initial and final substances are well ccharacterized
- The chemistry of polymers under re-entry conditions (combustion/pyrolysis conditions) can lead a wide range of by products; there is not only one chemical reaction.
- The final composition can be evaluated if the thermodynamic properties of the polymer is well known. (Advanced Thermal Analysis System ATHAS Data Base)

$$PTFE \equiv (C_2F_4)_n \xrightarrow{500-700\ ^{\circ}C} CF_4 \quad C_2F_4 \quad CHF_3 \quad CO_2 \quad HF \quad CH_2F_2 \quad C_2F_6 \quad CH_3F$$

The thermodynamic properties of the products are well characterized.
The final composition can be estimated by Gibbs-Energy minimization IF the thermodynamic properties of the PTFE is known.

$$PVC \equiv (CH_2CHCl)_n \longrightarrow CO_2 \quad HCl$$

chlorometane, benzene, chlorobenzene, xilene, toluene, naphthalene, indene

Atmospheric simulations – short term analysis by EMAC

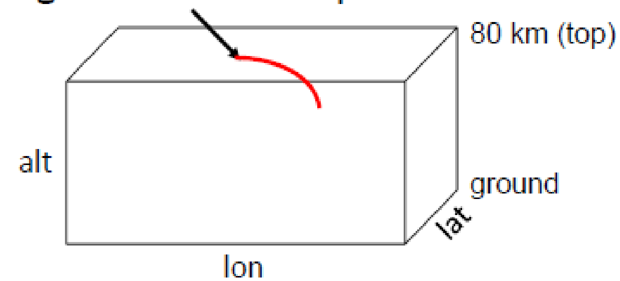
Short term analysis by EMAC state-of-the-art Earth-System Model EMAC in the latest version (Jöckel et al.)

- to investigate transport pattern of substances from S/C demise
- to calculate changes in the atmospheric composition.
- The model EMAC includes detailed stratospheric and tropospheric chemistry, as well as liquid phase chemistry, and various aerosol models.
- Processes such as cloud formation, convection, lightning, dry- and wet deposition, sedimentation, and radiation are parameterised. The model's resolution is flexible.

Simulation setup

ECHAM5 (general circulation model) resolution	: T42/L90 (2.8*2.8 deg, up to 1.0 Pa)
Chemical interaction	: Included by MECCA sub model
Time step	: 12 min
Simulation period	: **2 – 3 months**
Emission data	: Available substances data derived from Task 4 are used
Emission data format	: NetCDF (in flux; lat, lon, alt, time=1)

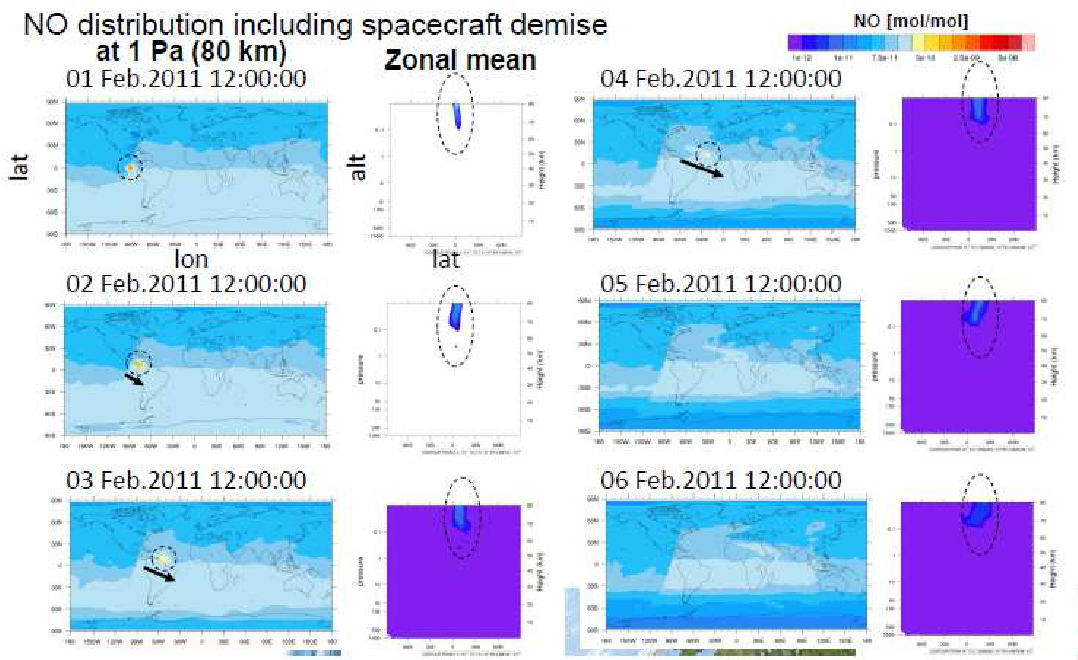
Emissions generated from spacecraft demise



Atmospheric simulations – short term analysis

Sensitivity analysis

- To investigate changes in transport patterns of substances with respect to location / seasons



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Atmospheric simulations – long term

- Analyse the atmospheric and climate impact of spacecraft demise.
- EMAC long term simulations calculates Radiation Forcing (RF) changes including emission from spacecraft demise event
- While the Air-Clim (climate-chemistry response model) calculates the climat impact

↓ Output from EMAC

1-year RF change (2011)

↓ Input for AirClim

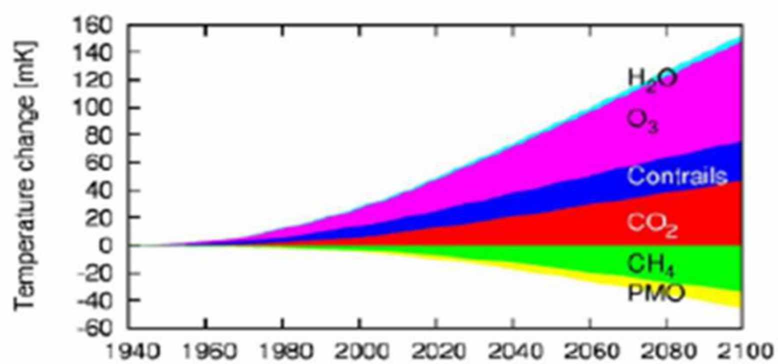

Figure 19: Change in near-surface air temperature (mK) caused by aviation as an example for climate response modelling

Thank you

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