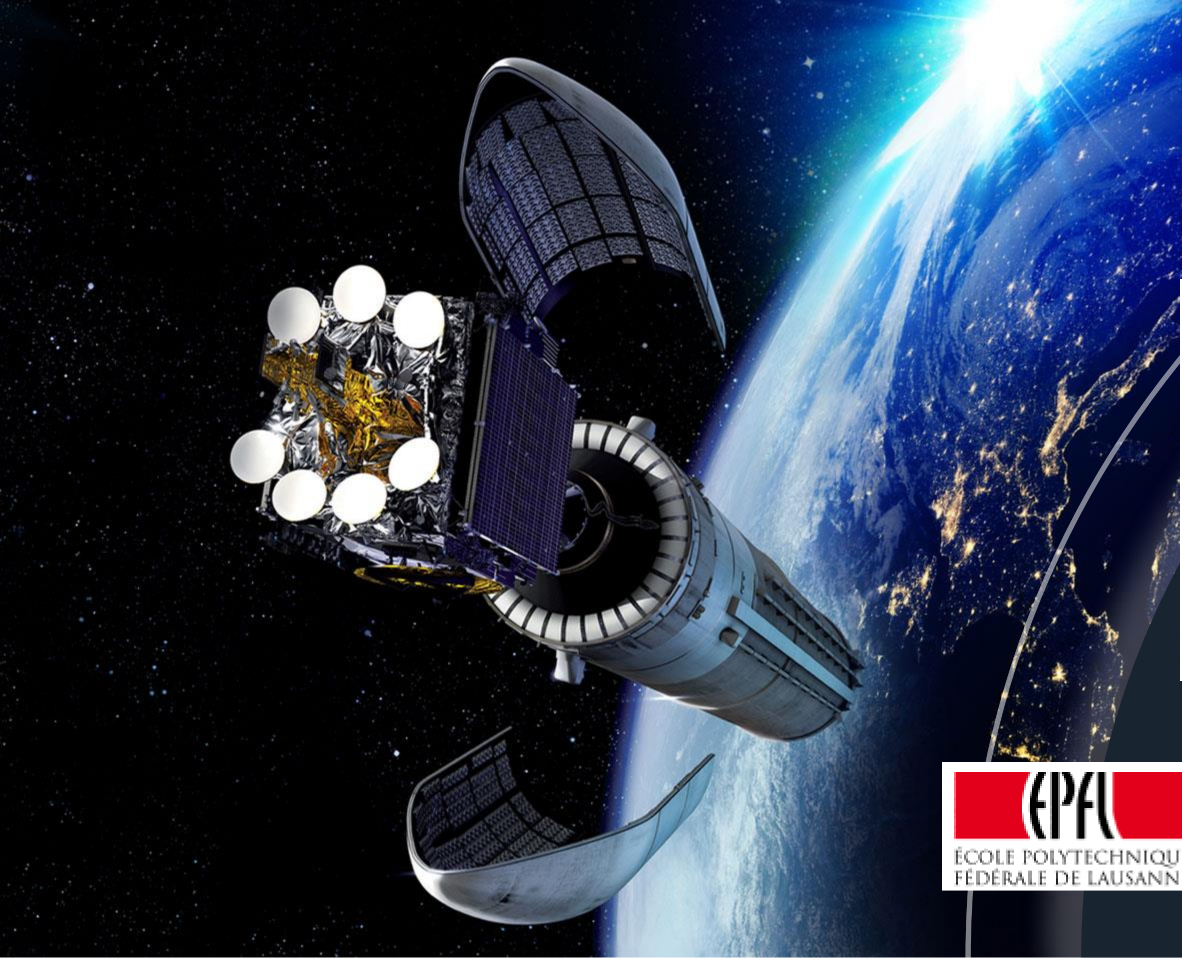

ARA
Atmospheric Re-entry Assessment

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

DLR

ThalesAlenia Space
a Thales / Leonardo company

Study Team

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Study Goals

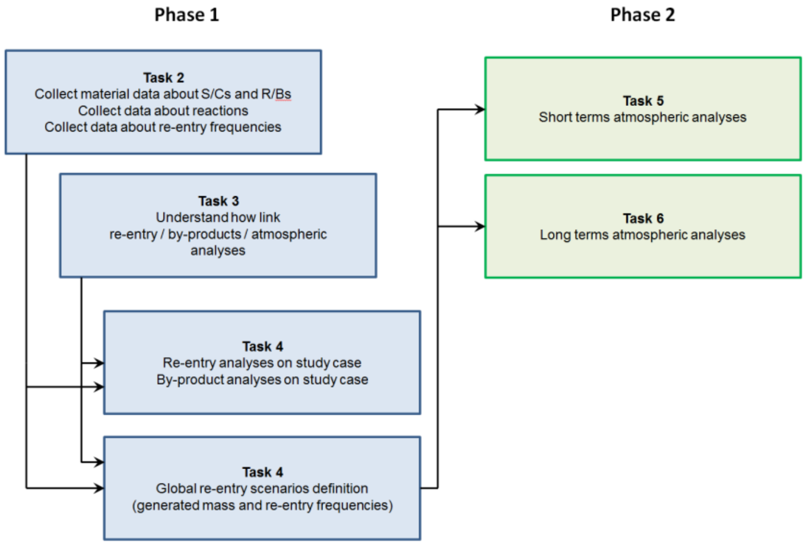
The scope of the Study is the investigation of the potential impacts on the atmosphere and on climate, caused by gases and particles released during the re-entry of spacecrafts and rocket upper stages

- Task 2 focused on:
  - detailed definition of the materials used for spacecraft and upper stages had been carried out
  - an assessment of the re-entry frequency expected over the coming decades will be performed.

- Task 3 focused on the definition of the modelling requirements for both the aerothermodynamic evaluation and the climate models

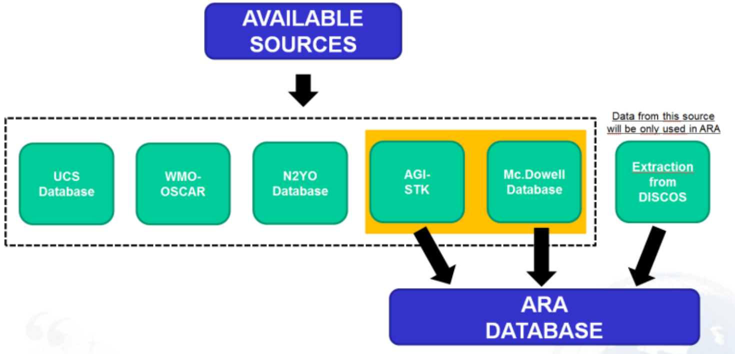
- Task 4 focused on:
  - a detailed re-entry and product analysis (and the associated sensitivity) on a select study case
  - Definition of a global re-entry scenario, using the data related to the study case and the sensitivity, as well as the re-entry frequency assessment

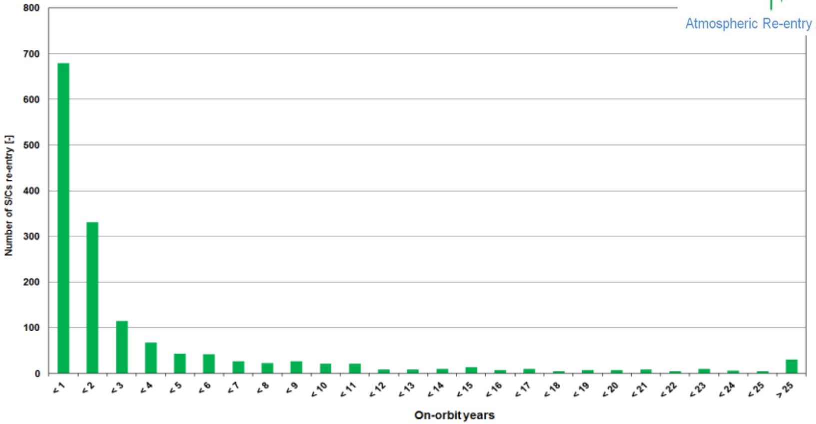
- The generated data will be used as an input for the second phase of the study (Task 5 and 6), focussed on the short-term and long-term assessment of the atmospheric impact of spacecraft demise.

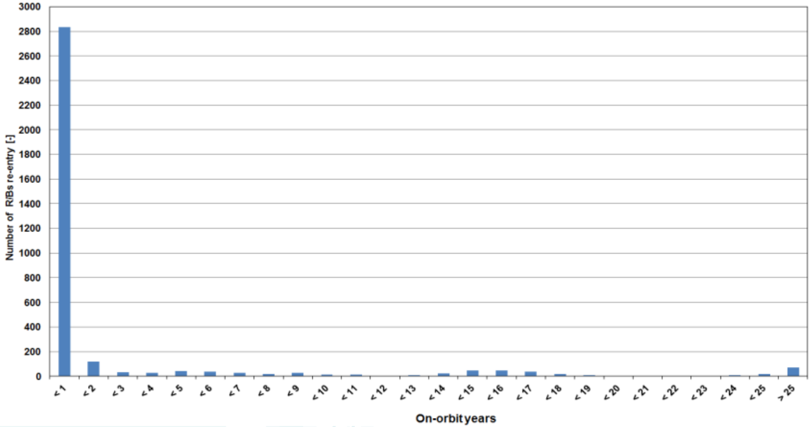


Task 2: S/Cs & R/Bs data survey

Goal / Hypotesis: understand to future re-entry scenario through past data, available from TASinI database







- For both R/Bs and S/Cs a re-entry rate is predictable
- The driving characteristics (mass, inclination, mission type) for both R/Bs and S/Cs are available

→ **All the data required for the definition of a global re-entry scenario are available**

Task 2: Identification of critical materials & critical reactions

- Goal / Hypotesis: understand to future re-entry scenario through past data, available from TASinI database
- Identification of material compostion of S/Cs and R/Bs
- Understandig of TADAP modelling vs reality

Identification of critical reactions

Assuming ad –hoc mass balance from SoW identify the main metals and their proportions.

- metal oxides decompose the ozone at room temperature.
  The activity of the catalyst depends on the nature of the metal oxide and in increasing order of activity it can be classified as:

  $MnO_2 > NiO > Co_3O_4 >> Fe_2O_3 > Ag_2O > Cr_2O_3 > CeO_2 >> V_2O_5 > MgO > CuO > MoO_3$

  Al_2O_3, TiO_2 photochemical activity against the O_3[RD67].

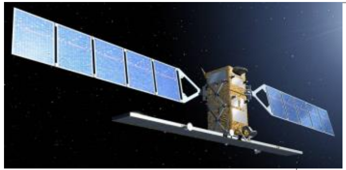
  main by-products to be considered :

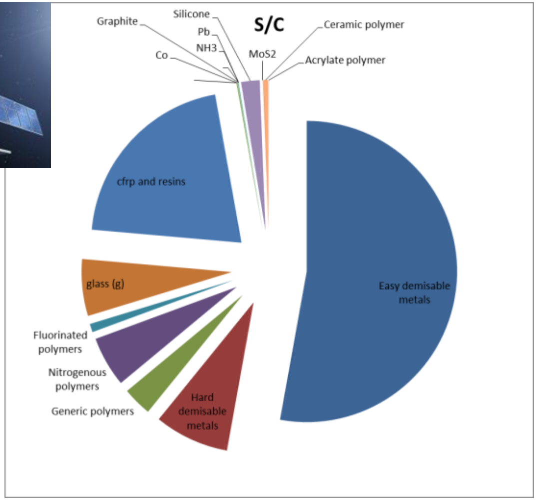
  Al_2O_3, TiO_2, NiO, Fe_2O_3, Cr_2O_3, Co_3O_4, Ag_2O, CuO

- Organics: base (polymers, paints, fibers, etc.)
  PTFE can be decomposed in air above 500 ºC forming CO2 , HF , H2O, etc.
  but in pyrolytic conditions, in sub-stoichiometric conditions a wide range of halocarbons can be formed [RD68], i.e. C2F2, C2F4, CF4, CH3F, C2F6, which can have a catalytic effect on ozone depletion.

Mass in DML are provided according to the following table, average values were assumed → DML used to derive % of composition → All masses were rescaled to match the component mass.

Status	Explanation	min	average	max
W0	0 g to <1 g	0.0001	0.0005	0.001
W1	1 g to <10 g	0.001	0.005	0.01
W2	10 g to < 100 g	0.01	0.05	0.1
W3	100 g to <1 kg	0.1	0.5	1
W4	1 kg to <10 kg	1	5	10
W5	10 kg to <100 kg	10	50	100



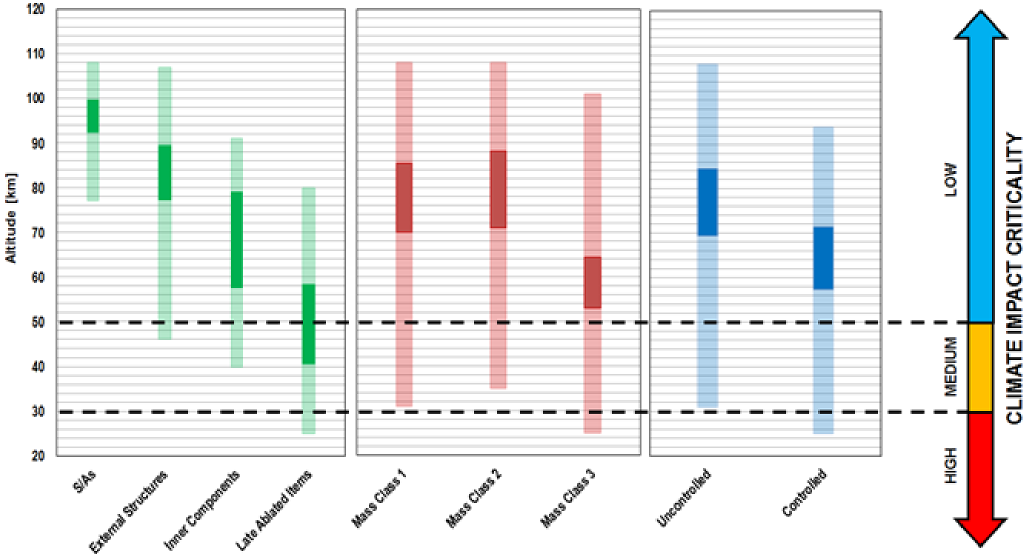


Task 2: Identification of typical altitude ranges of spacecraft demise

Atmospheric Re-entry Assessment

Identification of the altitude ranges in which spacecraft typically demise

Identification of the altitude ranges in which a release of anthropogenic substances is most critical



Mass Class 1 (0-500 kg) demise typical altitude ranges

- TADAP analyses
  - Simulations about specific items (D4OP Task 1)
  - Simulations about some relevant O/P payloads (D4OP Task 2)
- SCARAB analyses
  - CarbonSat uncontrolled re-entry analysis (D4OP Task 2)
  - BeppoSAX uncontrolled re-entry analysis (BeppoSAX re-entry analysis)
  - GOCE uncontrolled re-entry analysis
  - TERRASAR-X uncontrolled re-entry analysis
- DRAMA analyses
  - E-deorbit Chaser controlled re-entry analysis (e-deorbit Phase B1)
  - E-deorbit Chaser uncontrolled-like re-entry analysis (e-deorbit Phase B1)
  - E-deorbit Chaser uncontrolled re-entry analysis (e-deorbit Phase B1)
  - DRAMA Test Satellite (DRAMA Final Report)
- SAM analysis
  - DRAMA Test Satellite analysis with SAM
- DAS analysis
  - TERRASAR-X uncontrolled re-entry analysis

Mass Class 2 (1500-2500 kg) demise typical altitude ranges

- TADAP analyses
  - S-1A uncontrolled re-entry analysis (ARA Proposal)
- SCARAB analyses
  - S-1A uncontrolled re-entry analysis
  - S-1C/D uncontrolled re-entry analysis

Mass Class 3 (>2500 kg) demise typical altitude ranges

- SCARAB analysis
  - ATV controlled re-entry analysis
  - E-deorbit ENVISAT controlled re-entry analysis (e-deorbit Phase B1)
  - E-deorbit ENVISAT uncontrolled-like re-entry analysis (e-deorbit Phase B1)
- ORSAT analysis
  - Terra Satellite analysis

Task 3: Re-entry / Atmospheric analyses armonization

Atmospheric Re-entry Assessment

To understand how atmospheric analyses work

- **Common data format**
  - NetCDF (Network Common Data Format)
- **Specific emission data**
  - Trajectories (location and altitude)
    - Coordinates in LAT & LON
    - Pressure altitude in [hPa]
  - Time (not necessary)
  - Emission data as flux [kg m^{-3} s^{-1}]
  - Available data of the substances derived from WP4000 will be used in WP5100 & 5200.

```
netcdf example_ARA {
dimensions:
    lon = 720 ;
    lat = 360 ;
    lev = 25 ;
    time = UNLIMITED ; // (1812 currently)
    iklev = 26 ;
variables:
    float lon(lon) ;
        lon:standard_name = "longitude" ;
        lon:long_name = "longitude" ;
        lon:units = "degrees_east" ;
        lon:axis = "X" ;
    float lat(lat) ;
        lat:standard_name = "latitude" ;
        lat:long_name = "latitude" ;
        lat:units = "degrees_north" ;
        lat:axis = "Y" ;
    float lev(lev) ;
        lev:standard_name = "air_pressure" ;
        lev:long_name = "altitude" ;
        lev:units = "hPa" ;
        lev:positive = "down" ;
        lev:axis = "Z" ;
    double time(time) ;
        time:standard_name = "time" ;
        time:units = "days since 1850-01-01 00:00:00" ;
        time:calendar = "standard" ;
    float NOx_flux(time, lev, lat, lon) ;
        NOx_flux:units = "kg m-3 s-1" ;
    float pressi(iklev) ;
        pressi:units = "hPa" ;

data:

lon = 0.25, 0.75, 1.25, 1.75, 2.25,...;

lat = -89.75, -89.25, -88.75, -88.25, -87.75,...;

lev = 977.3322, 908.5836, 843.7991, 782.8019, 725.4205,...;

NOx_flux = 1.101807e-18, 1.101807e-18, 0, 0, 0,...;

pressi = 1013.25, 942.4511, 875.7069, 812.8379, 753.6697,...;

}
```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Task 3: Re-entry / Atmospheric analyses armonization

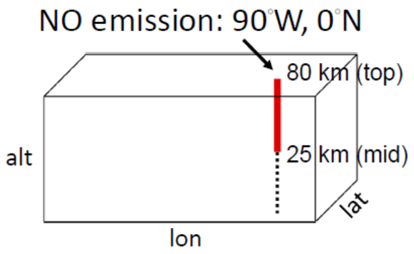
ARA Atmospheric Re-entry Assessment

- **Output quantities**
  - Output quantities, contents, frequencies, statistical values (instantaneous data, average w.r.t. time of data, etc.) can be flexibly changed.
  - NO, NO_x, NO_y, O_3, loss of O_3 and production of O_3

- **Simulation conditions (day/season)**
  - different circulation pattern and/or chemical activity in the upper atmosphere
  - a specific date when a satellite re-entry was implemented in the past
  - seasonal classification (summer/winter)

Simulation set-up

ECHAM5 (general circulation model) resolution	: T42/L90 (2.8*2.8 deg, up to 1.0 Pa)
Time step	: 12 min
Calculation term	: 1 month (Feb.01.2011-Mar.01.2011)
Emission type	: NO, column–emission source
Emission data format	: NetCDF 'NO_flux (lat, lon, alt, time=1)'
Chemical interaction	: Included by MECCA Model



Task 3: Re-entry / Atmospheric analyses harmonisation

Atmospheric Re-entry Assessment

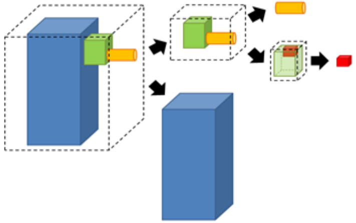
To understand how re-entry analyses work: TADAP

TADAP has been applied to TASinI internal activities, and also in the context of ESA study as:

- Design for Demise
- Demisability for Optical Payloads
- Atmospheric Re-entry Assessment
- e.Deorbit - phase B1

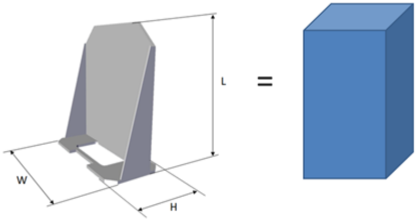
Initial orbit
- Possibility of set up different Trajectory Earth Fixed initial data

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
- When more items are simulated, the aerodynamics is computed by a representative envelope, which is automatically defined in each step of the simulation
- 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
- Shapes, dimensions and position close as-much-as-possible to the real objects



Connections
- Multiple connections are generally modelled
- The weakest connections can be modelled with a glue layer (e.g. mirrors on their mounts)

Materials
- Adoption of the most representative material for each shape
- Metal-like modelling for heating and ablation

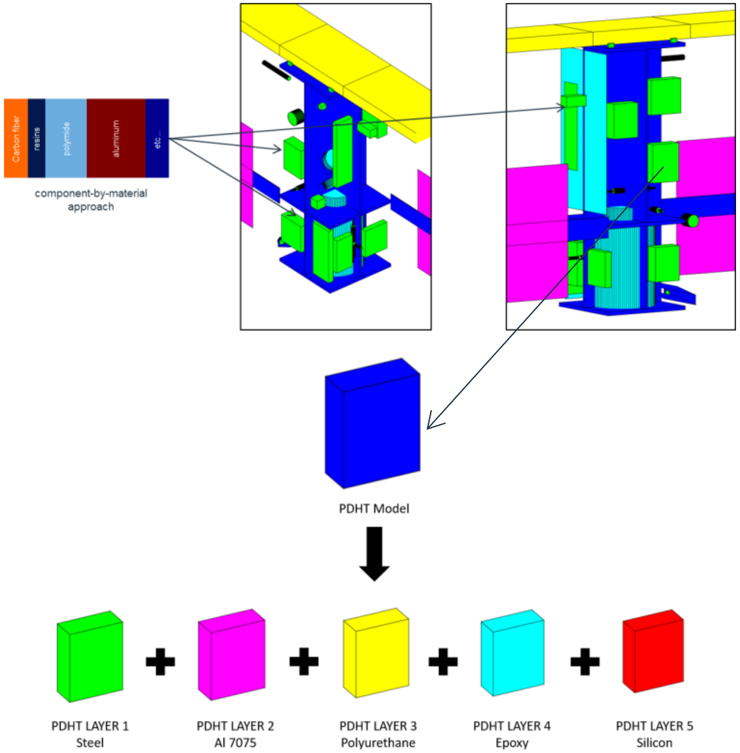
Masses
- The masses of single objects are close as-much-as-possible to the real objects.
- Mass balance (i.e. total masses almost equal at platform and payload level).
- Adoption on "thermic/dummy" masses to obtain the above-mentioned balance (i.e.: all the items that are not modelled in detail, and included in large aluminium masses to obtain the correct mass)

Granularity
- Granularity decided by User: current limit ca 250 item per model

→ **No reason to allocate efforts for exstended "glue code" developments.**

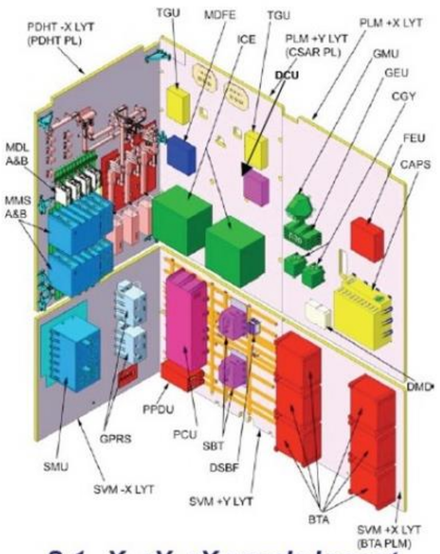
Task 4: TADAP modelling

- 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;
  - each TADAP layer of the same S/C critical component has a ***physical connection*** to all the other ones but a thermal connection between internal layers is not implemented because of the high time and cost of computation process. ***Thermal connection*** is implemented between one layer of different elements, generally the metallic case, which is called *representative layer*.
- Generally a number between 5 and 10 of different materials (and thus 5-10 layers) are modelled for each S/C component to represent at least the most critical materials for atmospheric impact.



Task 4: TADAP modelling

Atmospheric Re-entry Assessment



S-1 –X, +Y, +X panels lay-out (+X panel rotated 90°)

AVS – Avionics S/S
BTA – Battery
CAPS – C-Sar Antenna Power Supply
FDV – Fill & Drain Valve
FVV – Fill & Vent Valve
GPS Lagrange Receiver
GYRO - Redundant Three axes sensor
LT – Propellant Tank
LV - Latching Valves
MGM - Magnetometer
MGT - Magneto Torquer
PCU – Power control unit
PDHT – Payload Data Handling & Transmission
PPDU – Power Protection & Distribution Unit
PT – Pressure Transducer
PT – Pressure Transducer
RCT – Thrusters
RWA - Reaction Wheels assembly
SADA - Solar Array Drive Assy
SAR – Synthetic Aperture Radar
SAS - Sun sensor
SAW – Solar Array Wing
SIE – SAR Internal Electronics
SMU - Spacecraft Management Unit
STT - Star Tracker
TT&C – Telemetry Tracking & Control

S/C COMPONENT	TADAP COMPOUND
BTM	BTT
GPS	BXD
SMU	
SBT	
FOAMO	BXU
ICE-A	
ICE-CON	
ICM	
MDFE	
SESI	
TGU	
TGU DC/DC	
FDV	FDV
LF	
LV	
PIP	
PT	
FSS	FSS
GYRO	GYRO1
HEAT PIPES	HTPP
MGM	MGM
MGT	MTQ X/Y/Z I + MTQ X/Y/Z O
PCDU	PCDU
DSHA	PDHT
TANK	PTANK

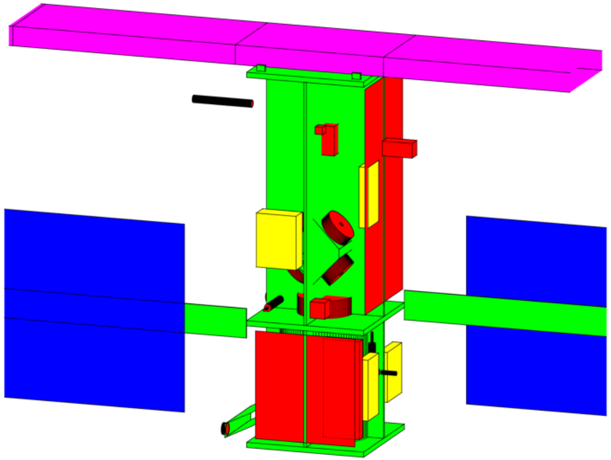
Task 4: TADAP modelling

Structural elements (example)

ELEMENT TYPE	TADAP NAME	TADAP SHAPE	MASS [kg]	MATERIAL
Structural Panel	SVMAP	BOX	17.6765	Honeycomb
CB Cone	ICONE	CYL	22.3140	Honeycomb
Structural Panel	INTPL	BOX	17.6765	Honeycomb
Structural Panel	PLMSY	BOX	32.3459	Honeycomb
Structural Panel	PLMSX	BOX	32.3459	Honeycomb
Structural Panel	SVMSY	BOX	15.6793	Honeycomb
Structural Panel	SVMSX	BOX	15.6793	Honeycomb
Structural Panel	ZPANE	BOX	17.6765	Honeycomb
Structural Panel	SVMXP	BOX	14.5077	Honeycomb
Structural Panel	SVMYP	BOX	14.5077	Honeycomb
Structural Panel	SVMYM	BOX	14.5077	Honeycomb
Structural Panel	SVMXM	BOX	14.5077	Honeycomb
Structural Panel	PLMXP	BOX	29.3073	Honeycomb
Structural Panel	PLMYP	BOX	29.3073	Honeycomb
Structural Panel	PLMXM	BOX	29.3073	Honeycomb
Structural Panel	PLMYM	BOX	29.3073	Honeycomb

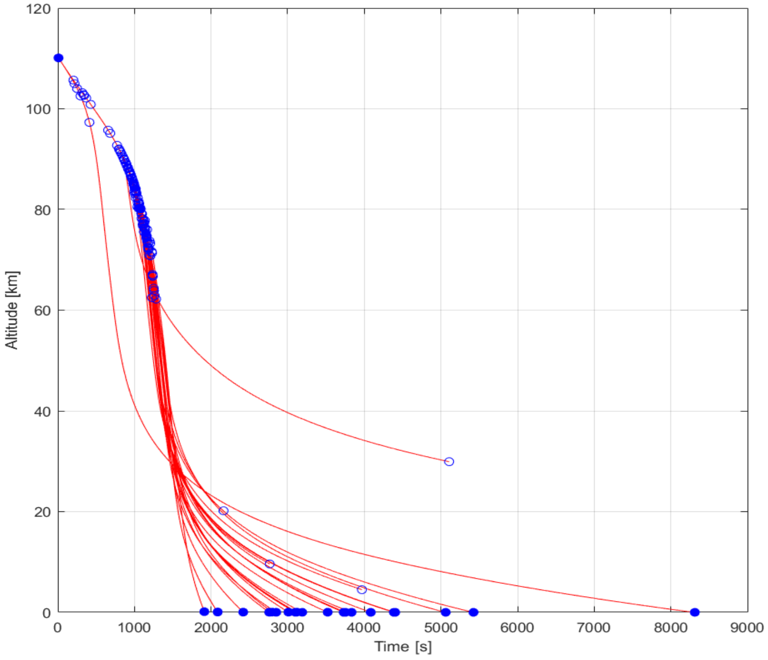
Components (example)

Fine Sun Sensor	FSS11	CYL	0.0354	Titanium
	FSS12	CYL	0.4466	Al 7075
	FSS13	CYL	0.0417	Polyolefin
	FSS14	CYL	0.0032	Polyurethane
	FSS15	CYL	0.0354	Glass
	FSS16	CYL	0.0542	Epoxy
	FSS17	CYL	0.0096	Silicon



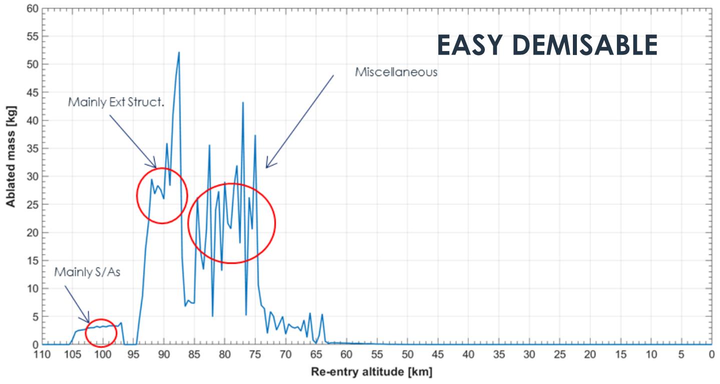
Task 4: TADAP results

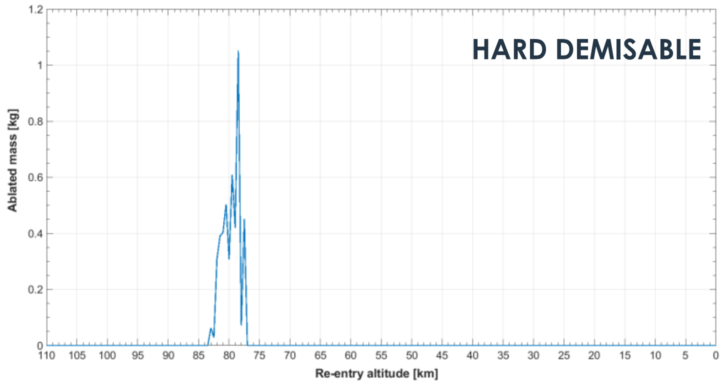
UNCONTROLLED BASELINE

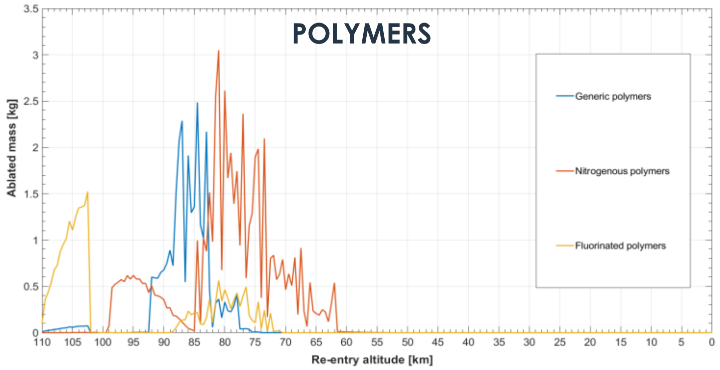


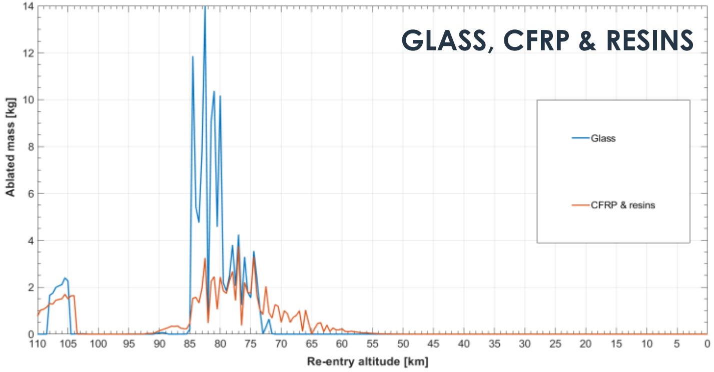
- SENTINEL-1 fragmentation tree. Every blue dot represents the end-of-life time for a given debris at a certain altitude.
- Major fragmentation occurs for an altitude range of 90-70 km.
- Since current TADAP version does not take into account mechanical fragmentations, S/As separation from main S/C is triggered at 110 km, shortly after simulation's start (SCARAB heritage).
- Since current TADAP version does not take into account mechanical fragmentations, CSAR separation from main S/C is triggered at 75 km (SCARAB heritage).

Task 4: TADAP results







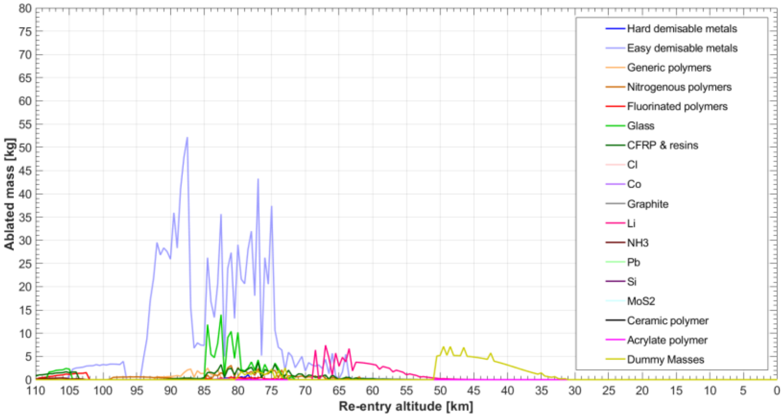


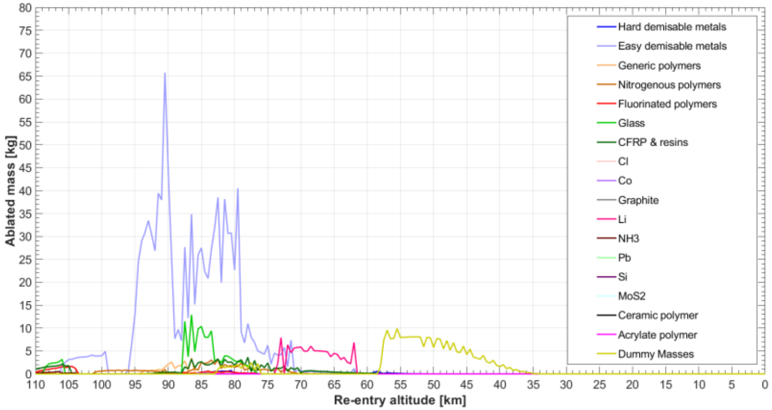
ARA Atmospheric Re-entry Assessment

Task 4: TADAP results

UNCONTROLLED SIMULATION - INCREASED CONVECTIVE HEAT FLUX CASE (BY 20%)

UNCONTROLLED BASELINE CASE ABLATED MASS [kg]	*+20% CONVECTIVE HEAT FLUX SENSITIVITY CASE ABLATED MASS [kg]*
1614.57	1751.62

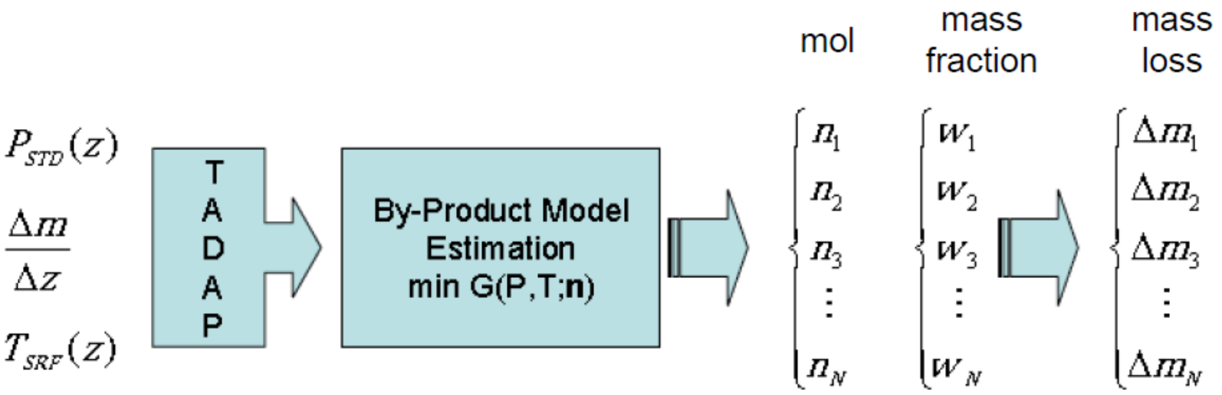




A comparison between ablated mass trends for the two analyses shows a greater amount of ablated mass of easy demisable metals and dummy masses for the sensitivity case. Ablation occurs for the sensitivity case with an anticipated altitude gap of about 5 km.

Task 4: By-Products modelling

General Approach



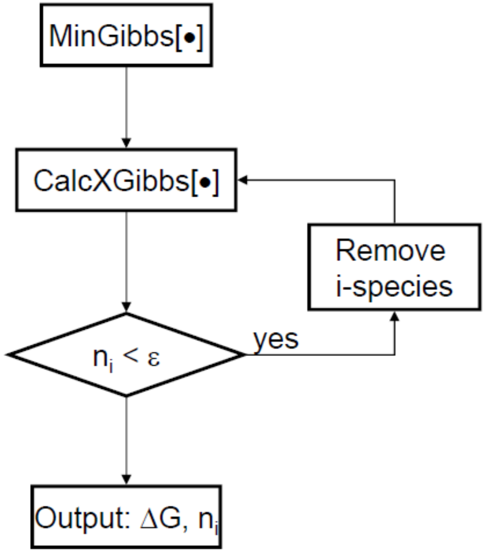
P_{STD} : Standard atmosperic pressure

T_{SRF} : Surface temperature

$\frac{\Delta m}{\Delta z}$: Ablation gradient

Task 4: By-Products modelling

By-products



Element Base Definition (AA7075 Alloy)

NASA — National Aeronautics and Space Administration; ARGONNE National Laboratory; TECHNION Israel Institute of Technology

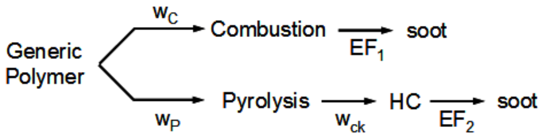
```
elements = Sort[{"AL", "CU", "ZN", "MG", "CR", "O", "N"}];

asubst = AllSubstList[NASAdb[[All, 6]], elements];

{gas, cnd, ion} = Phases[NASAdb, asubst, True];

Gases: {AL, ALN, ALO, ALO2, AL2, AL2O, AL2O2, AL2O3, Cr, CrN, CrO, CrO2, CrO3, Cu, CuO, Cu2,
  Mg, MgN, MgO, Mg2, N, NO, NO2, NO3, N2, N2O, N2O3, N2O4, N2O5, N3, O, O2, O3, Zn, CrO, CuO, Cu2, NO2,
  NOO, N2O2, N2O2, N2O, N2O, N2O3, N2O3, N2O4, N2O4, N2O5, N3, N4, N4, N4, O*, O2*, O3c, O4, ZNO}

Condensed: {AL(cr), AL(L), ALN(cr), ALN(L), AL2O3(a), AL2O3(L), Cr(cr-a), Cr(cr-b), Cr(L), CrN(cr),
  Cr2N(cr), Cr2O3(I'), Cr2O3(I), Cr2O3(I), Cr2O3(I), Cr2O3(L), Cu(cr), Cu(L), CuO(cr), Cu2O(cr),
  Cu2O(L), Mg(cr), Mg(L), MgAL2O4(cr), MgAL2O4(L), MgO(cr), MgO(L), Mg3N2(cr), Zn(cr), Zn(L), ZnO, ZnO}

Ionic: {AL+, AL-, ALO+, ALO-, ALO2-, AL2O+, AL2O2+, Cr+, Cr-, CrO3-, Cu+, Cu-, Mg+, N+, N-, NO+,
  NO2-, NO3-, N2+, N2-, N2O+, O+, O-, O2+, O2-, Zn+, CrO3-, NO-, NO2+, NO2+, NO2-, NOO+, NOO-,
  NO3+, NO3-, N2-, N2O+, N2O-, N2O+, N2O3+, N2O3-, N3+, N3-, N4-, O3+, O3-, O3c+, O3c-, O4+, O4-}

aa7075 = Join[gas, cnd];
```

141 chemical species

```
Cu → 0.0009569536180975966
NO → 0.0001633592321623629
N2 → 0.7049531302445612
O2 → 0.11042140540396096
Zn → 0.002836381225715734
AL(cr) → 0.
AL2O3(a) → 0.046349315929057874
Cr(cr-a) → 0.
Cr2O3(I) → 0.00008771822151206354
Cu(cr) → 0.
Mg(cr) → 0.
MgAL2O4(cr) → 0.003627840149668506б
Zn(cr) → 0.
```

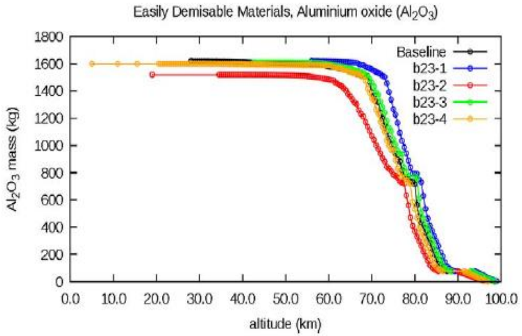
6 chemicals
+ air

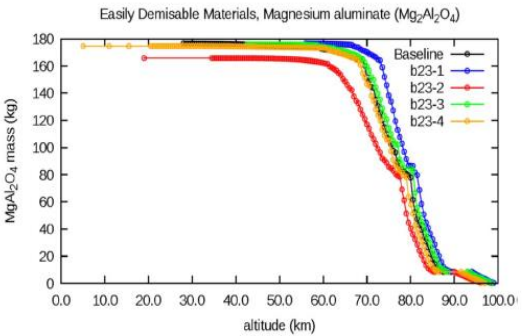
Soot formation

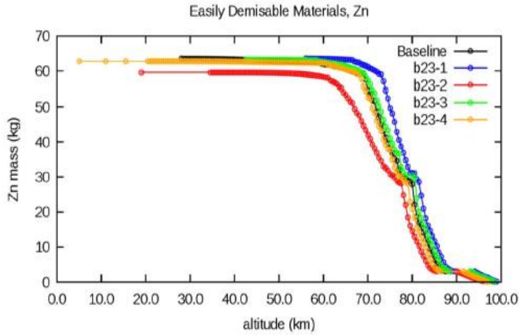


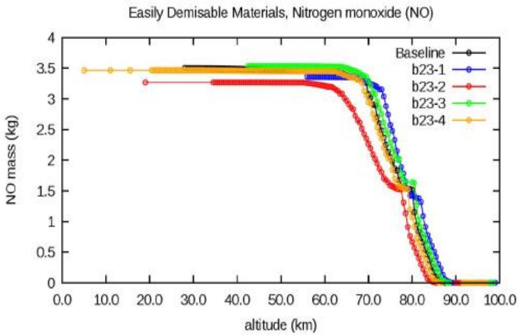
Task 4: By-Products results

EASILY DEMISABLE METALS

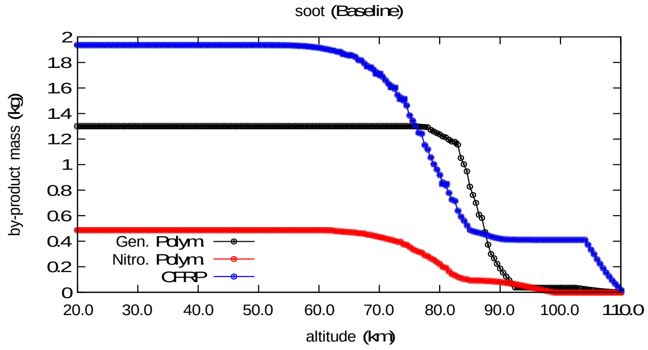








SOOT



Task 4: By-Products results

ARA
Atmospheric Re-entry Assessment

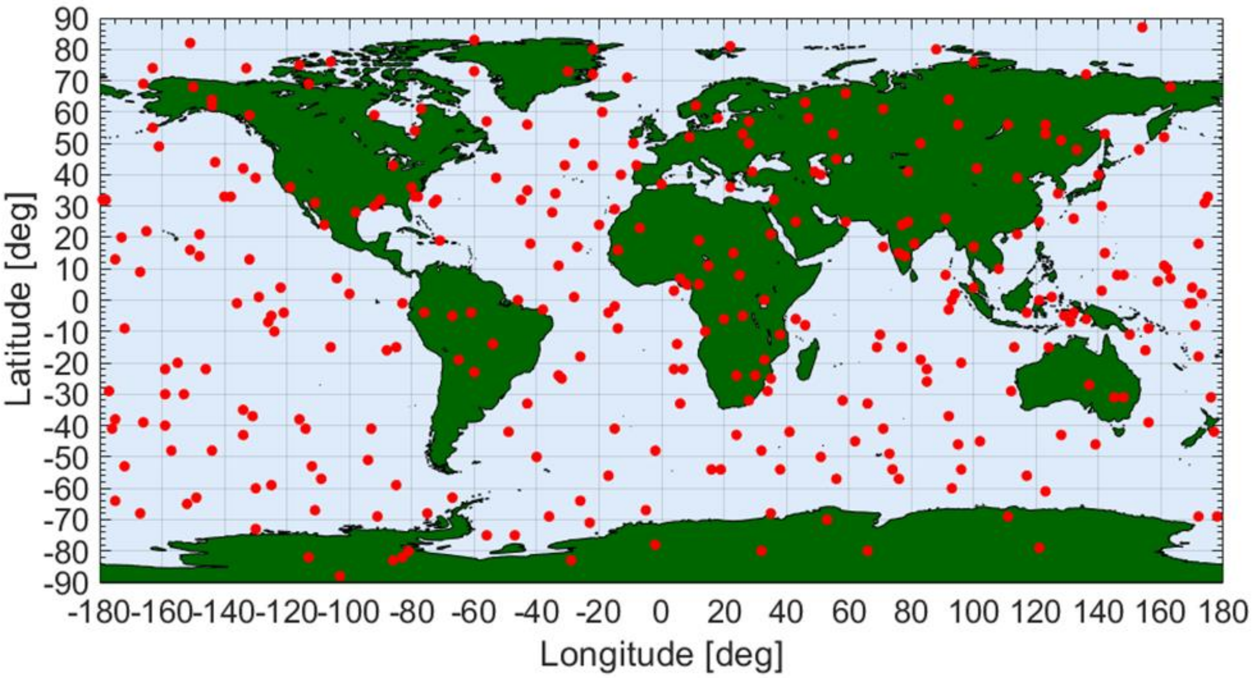
CONCLUSIONS

- The most stable by-products chemicals can be evaluated with the thermodynamic properties of the original compounds (equilibrium state)
- Knowing the ablated mass a assuming super-stoichiometric conditions, the mass of produced by-products can be evaluated along the re-entry trajectory.
- Polymers and batteries by-products can be chemically active against O_3 decomposition.

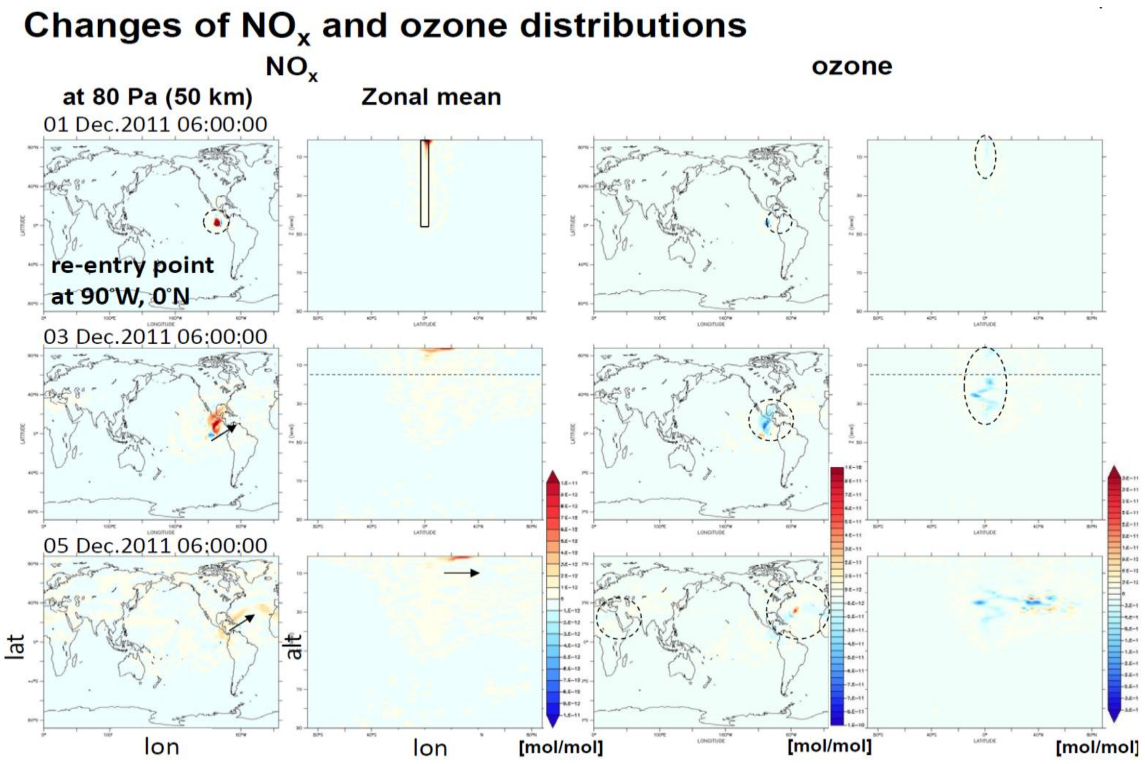
Task 4: Scenarios definition

By **combining & rescaling** the data from released substances and data from re-entry statistics, 3 different scenarios are developed for Task 5 and 6 analyses:

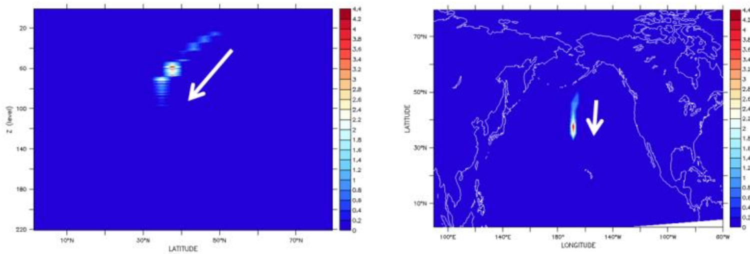
- Short terms scenario (2 months – current re-entry rate)
- Long terms scenario(12 months – current re-entry rate)
- Long terms scenario(12 months – re-entry rate including mega constellations)



Task 5: Examples



Input data example: NO emission [kg] from 2M_Event_1

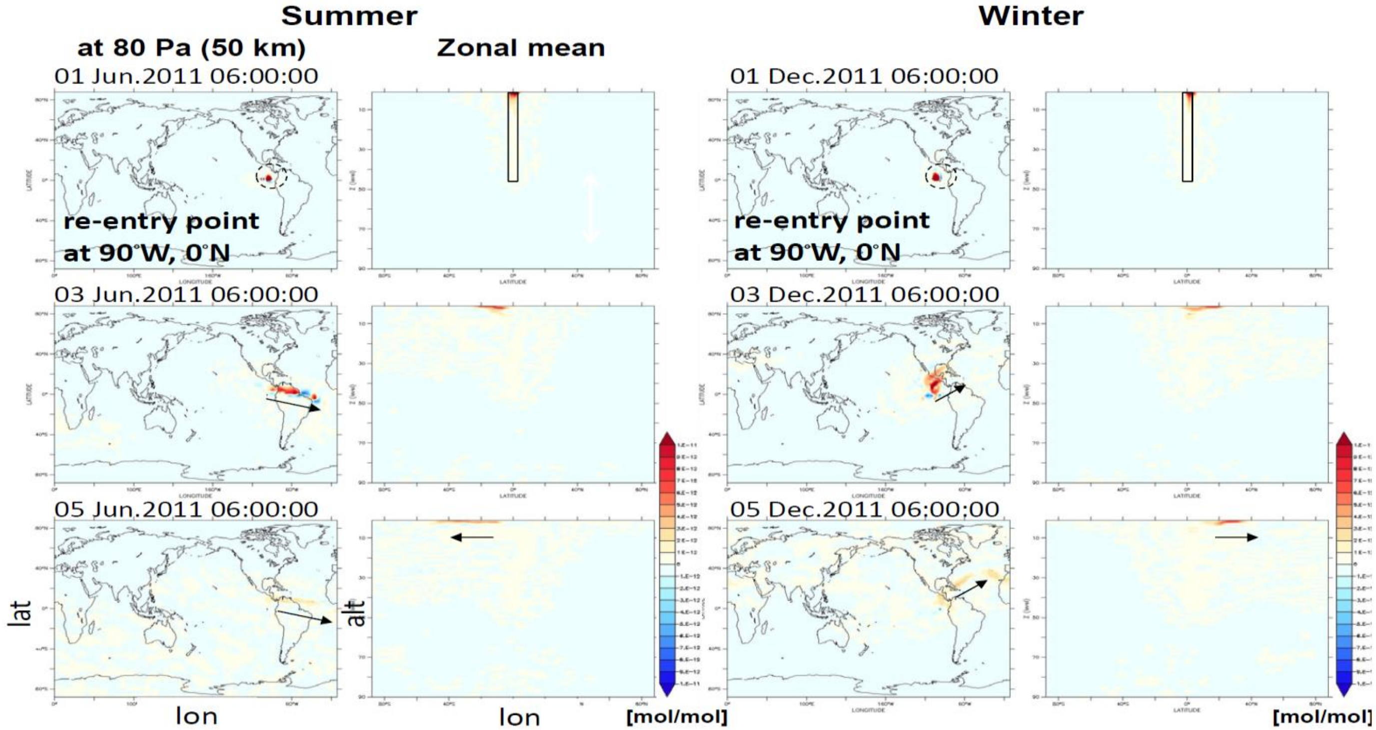


Total NO Emission: 83.4 [kg]

NB: the impact of particle on atmospheric is taken into account

Task 5: Examples

Changes in transport pattern of NO_x by season



Conclusions & Way forward

- First time the issue of impact of destructive re-entry is assessed

- ARA study represents an high challenge, since 4 very different disciplines have to interact each other: space activity statistic, re-entry analyses , by-product analysis, atmospheric analyses – pushing up the analyses capability (e.g. Relevant occasion to push-up the capability of re-entry low-fidelity codes)

- At the present moment, the second phase of the Study is ongoing, so not specific conclusions on the impact on atmosphere can be already derived.

- Creation of knowledge-net and team-net for any potential future activity as multidisciplinary as ARA