THE APPROACH TO CASUALTY RE-ENTRY RISK MITIGATION IN COSMO-SkyMed CURRENT AND FUTURE GENERATIONS

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ABSTRACT

The European Member States are called to strictly apply the Space Debris Mitigation ESA normative to new Spacecraft design for launches from 2020. In the frame of Italian Space Agency and Ministry of Defense Programme for COSMO-SkyMed Second Generation Satellites, Thales Alenia Space Italy as Large System Integrators performed a Space Debris casualty re-entry risk assessment with the DRAMA tool.

In the paper the evolution of the analyses techniques to support the design review and assessment will be described starting from differences between the previous Cosmo Skymed Design and the second Generation one.

For the next SC generation (launch from 2020) TASI is studying the potential application of technologies in Spacecraft Design that could allow improvements in uncontrolled and controlled re-entry according to on-going assessment at European level.

Uncontrolled re-entry enabling technologies for Propulsion and Power Passivation and Design for Demisability are under trade-off for TASI PRIMA Platform Satellites in terms of improvements aimed at reduction of the number of re-entering fragments on ground which can be obtained by either System level solutions (e.g. anticipated separation of some SC parts) or S/S and equipment level solutions (e.g. improved technologies implementation).

Concerning controlled re-entry, some dedicated Spacecraft functions are envisaged aimed at reducing the casualty area to a confined and known zone over the Ocean, by improving capabilities in propulsion, AOCS (e.g. bigger or additional tanks, actuators apt to control the Spacecraft in all manoeuvre phases) and at mission and operations level (i.e. communication with ground and on-board autonomy).

CGS lesson learned, in term of re-entry assessment, will be described, highlighting the actual design constraints together with an initial set of internal guideline to further improve future satellite generations.

1 Analysis Techniques Evolution

The COSMO-SkyMed Constellation, composed of 4 satellites, is in orbit since 2010. The design Phase of the satellites took place in a period when the attention to Debris mitigation topics was starting to be deeply introduced to Industry at European level, in terms of guidelines for design and operations.

In this context the COSMO-SkyMed Programme started to assess the risks related to Spacecraft presence in-orbit and on-ground after End of Life by dedicated evaluations and analyses mainly in Engineering and Quality Areas.

1.1 Spacecraft FMEA

During nominal lifetime the Spacecraft internal sources of failure are identified and the FMEA at system level is performed assuming all the failure modes that have impact on the fulfillment of the mission.

A severity category classification is assigned to each identified failure mode analysed.

The monitored items for guidelines compliance are those for which during nominal lifetime a certain failure could cause a degradation of dependability down to the loss of control of the SC (loss of mission). The severity categories that address this type of risk are and "critical" and "catastrophic".

The assessment performed in COSMO-SkyMed mainly addresses:

- Bursting
- Loss of structural integrity
- Propellant leakage

All these aspects have been managed since the first COSMO-SkyMed generation performing dedicated tests with application of safety factors and by other specific provisions.

For example in case of Bursting failure mode due to :

- crack in pipe

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- over temperature
- micrometeoroid/debris impact

or leakage due to :

- micro-cracks in pipe
- welding defects
- micrometeoroids/debris impacts

a series of different actions have been put in place to reduce the severity (e.g. Proof test performed; manufacturing and integration provisions implemented; pollution/item corrosion criticality evaluated at system level; heat pipe designed according to safe life criteria; safety factors application in the structural design etc).

1.2 Collision Avoidance

To investigate the probability of catastrophic collisions with large debris, the total number of predicted impacts with debris with a diameter greater than 10 cm is typically evaluated with both the ESABASE2/Debris (with MASTER2009 debris environment) and the MASTER2009 software tools.

This activity, performed for CSG Programme, led to the definition of a collision avoidance strategy and allocate a quantity of propellant dedicated to collision avoidance.

Catastrophic Impact analysis is performed for determining the probability of the SC to impact with large particles. The main assumption is that such kind of impacts necessarily lead to the loss of the mission and consequences are therefore considered to be catastrophic. The results of the analysis express the potential of the SC to be hit by a large particle in terms of Probability Of No Impact (PNI) which is in the order of E-04 per year.

Although analysis results show no need for propellant dedicated to collision avoidance manoeuvres, a conservative approach has been chosen and a dedicated amount of propellant has been allocated.

Moreover a typical approach, foresees collision avoidance manoeuvres also in case of uncontrolled item (SC or any other object of size >10cm) approaching at a distance: in this case a preventive manoeuvre is performed in order to maintain a distance higher than a defined threshold between the SC and the Debris.

1.3 Disposal Operations and Passivation Strategies

The space debris policy is to design space vehicles in order to prevent the generation of space debris and to encourage the adoption of operational techniques which will limit the production of space debris during the operational phase, while ensuring consistency and compliance with the operational phase requirements and safety.

The disposal phase of CSG shall comply with the applicable standard for LEO missions according to it, no end-of-life disposal manoeuvre is required if the SC decays (uncontrolled) within 25 years.

The following strategies have been analysed for CSG in terms of Delta-V required by the manoeuvres, and consequent propellant mass for each option. In particular the following cases have been analysed:

- Natural orbital decay
- Direct De-Orbiting
- Delayed De-orbiting

The disposal strategies brief description is reported here-in after:

a) Natural de-orbiting: it means that there will be no intervention on the SC orbit after EOM.
b) Direct de-orbiting: By a direct de-orbiting manoeuvre, perigee is moved to a new altitude that leads the S/C to re-enter before completing an orbital revolution.
c) Delayed de-orbiting: By a delayed de-orbiting manoeuvre, the perigee is lowered to an altitude that leads the S/C re-entering by natural forces within a certain lifetime limit, i.e. 25 years.

For CSG satellites the delayed de-orbiting has been selected as disposal strategy and two mission solutions, de-orbit through circular and elliptical orbit solution have been further investigated.

a) Circular orbit: de-orbiting the satellite from a LEO nominal orbit to a lower circular orbit.
b) Elliptical orbit: placing the satellites into an elliptical orbit reducing the orbital perigee height.

The propellant budget estimated to perform the delayed deorbit strategy corresponds to lowering perigee down to an altitude that allows the re-entry on ground within 25 years.

For what concerns passivation strategies in COSMO-SkyMed and CSG, after the satellite reaches its disposal orbit, disposal measures are oriented to minimise the on board storage energy to avoid break-ups after the end of life.

All the sub-systems/items screened for potential SC break-up have been considered.

In particular all on-board actuators not yet used during nominal lifetime will be deactivated (switch-off).

Moreover the propellant tank and pipes will be emptied as much as possible by depletion burns.

Eventually the battery recharge will be minimised by discharging it and rotating solar array panels anti-sun. When the voltage drops under certain threshold the probability of battery re-charge remains very low.

1.4 Probability of successful disposal

The evaluation of the probability of successful disposal has been introduced for the second generation of COSMO-SkyMed.

The requirement interpretation is the following: the probability of successful disposal (disposal manoeuvre+ passivation) higher than 0,9 has to be evaluated as a conditional probability weighted on the mission success at the time disposal is executed.

The evaluation of the disposal success is equivalent to the computation of the satellite reliability over a duration Nd (that corresponds to the probability to operate the satellite at the end of the operational phase) and of the satellite reliability over a duration of (Nd + Dd) considering only S/C items needed for the disposal manoeuvers and passivation.

The computation can be essentially referred only to the platform reliability and it is for CSG compliant to requirement according to the defined disposal strategy.

1.5 Casualty Re-entry Risk Assessment

The scope of the casualty re-entry risk analysis is to assess the risks associated with the disposal of a space vehicle in Earth's atmosphere for either uncontrolled or uncontrolled re-entry.

An uncontrolled re-entry is defined as the atmospheric re-entry of a space structure in which the surviving debris impact cannot be guaranteed to avoid landmasses. The casualty risk is defined as the probability of serious injuries due to the re-entry of a space system.

For COSMO-SkyMed of First and Second generation the uncontrolled re-entry strategy is foreseen.

In addition, for the Second generation of SC dedicated analyses have been introduced by means of the tool DRAMA (Debris Risk Assessment and Mitigation Analysis) 2.0 developed by ESA. Results have been compared with those obtained by the DAS (Debris Assessment Software) tool.

The survivability and risk analyses provide a list of the objects which survive re-entry. Casualty area, which is a measure of the potential of each object to hurt people on Earth, has been calculated, and finally the risk associated has been obtained.

A single fragmentation event is considered, corresponding to the 78 km break-up altitude. No other fragmentations have been simulated, except for the solar panels (with the DRAMA code only). In fact, DRAMA can take into account the possibility of the Solar Array Wings to detach before the structure breaks up at a fixed altitude of 95 km. The DAS code does not allow the option of including a shear-off altitude for the detachment of Solar Arrays.

The principal factors in calculating the risk of human casualty from uncontrolled re-entries include the number of debris expected to reach the surface of the Earth, the kinetic energy of each surviving debris, and the amount of the world population potentially at risk.

The last factor is a function of both the orbital inclination of the space structure prior to re-entry and the year in which the re-entry occurs.

The re-entry risk assessment conducted has evaluated and compared results provided by using different world population models embedded in DAS and DRAMA and using either a no-nested and nested model SC models.

Consideration and simplification regarding the materials and shapes of the spacecraft items have been done.

The main assumptions selected are:

- Spacecraft nominal operational lifetime (7 years);
- Latitude averaged and inclination-dependent world population model;
- SAW detaching at a fixed altitude of 95 km, before the structure break-up at 78 km;

In general, the selected assumptions lead to the following reasonably considerations:

- DAS results are more conservative than DRAMA ones (also because of the lack of mass partial ablation and loss during re-entry. DAS considers an element to demised if its heat of ablation is exceeded otherwise its full mass is considered to have survived re-entry).
- Different world population models and different re-entry models lead to different casualty risk predicted by both codes, which however are quite close (with a mere 20% difference) and of the same order of magnitude of the requirement (i.e. E-04).

2 Potential Application of improvements for uncontrolled/controlled re-entry

In an International context increasingly engaged in Space Debris Mitigation Issues, both Industry and Space Agencies are addressing major Space Programmes towards the implementation of further improved approach to Spacecraft Design to fully reach Space Debris Mitigation Normative compliance.

The implications are foreseen at all levels, from analyses framework re-working and implementation in advanced tools for a better confidence in the assessment of risks, to design modifications aimed at reaching a higher degree of compliance with lower risks and higher performance.

2.1 Limits and Improvement needs for Casualty Re-entry Risk Assessment Tools

For what concerns software tools for the assessment of casualty re-entry risk, some limitations have been identified by COSMO-SkyMed Second Generation casualty re-entry risk analysis results evaluation in the use of DRAMA and DAS tools. The main are reported below:

Objects made of high thermal properties materials (CFRP, titanium)

Honeycomb panels: due to the limitation of the thermodynamic models currently implemented in the re-entry tools, Honeycomb Panels objects re-entry prediction often differs. It's worth to underline that the CFRP process of thermal decomposition is not comparable to the metal melting process and has not yet been implemented in any re-entry tools.

Balloon Effect

Large panels with an aluminium honeycomb core, such as PLM panels, experience "balloon effect": above a given area-to-mass thresholds an object (for example a heavy aluminium panel), which is typically expected to demise, survives instead.

Complex Shapes

Objects with complex shapes constructed of a single material can be modelled using equivalent area simplified shapes. Items constructed of multiple materials are more complex and typically require to increase the granularity of the models.

Ablation Criteria

The partial ablation of the items (not treated in DAS) explains the great difference between the estimated mass reaching on ground which according to DAS is 277.7 kg while according to DRAMA is 28.4 kg. DAS, indeed, considers an element to demise if its heat of ablation is exceeded otherwise its full mass is considered to have survived re-entry.

Fragmentation Events

A single fragmentation event is considered, corresponding to the 78 km break-up altitude. No other fragmentations can be simulated, except for the solar panels (with the DRAMA code only). In fact, DRAMA can take into account the possibility of the Solar Array Wings to detach before the structure breaks up at a fixed altitude of 95 km. The DAS code does not allow the option of including a shear-off altitude for the detachment of Solar Arrays.

Some of these limitations related to DRAMA and DAS software tools are overcome in new tools generation.

In particular for what concerns SC modeling in SC oriented tools, aerodynamic and aero-thermodynamic models and ablation models are much more detailed in already available tools on the market, while some issues still remain in materials modeling.

2.2 Potential Design Improvements

All solutions preliminary identified at International level are under definition and, in some cases, development, trying to cope with most of the needs for the different Spacecraft Classes on the market.

One of the main hypotheses that needs to be taken into account in the technologies screening is the reference Spacecraft Class of interest.

In particular the trend for Spacecraft sizing is evolving towards the use of smaller Platforms, and this will be taken into consideration also for the COSMO-SkyMed future generations.

In particular for the next and future generations of COSMO-SkyMed preliminary assessment is put in place to screen the available technologies for uncontrolled and controlled re-entry with respect to large and medium platforms, distinguishing between the ones that are going to be developed in the near future and the ones that are still just concepts with low TRL but of high interest for future Spacecraft design.

The enabling technologies pertain to two main categories of End of Mission disposal strategies:

- Uncontrolled re-entry
- Controlled re-entry

The selection between the two strategies mainly depends on Spacecraft Class and its capability to be compliant to the Casualty Re-Entry risk requirement.

For uncontrolled Re-entry the major improvements are in the field of Design for Demisability and Passivation.

The possible implementation of such solutions in COSMO-SkyMed next and future generations depend on:

- Envisaged specific improvements (mission and design dependent)
- Technology availability and TRL
- Technology adaptability and customization for COSMO-SkyMed Satellites

2.2.1 Uncontrolled Re-entry enabling technologies

Among uncontrolled re-entry improvements under assessment for COSMO-SkyMed future generations the Design for Demise interventions regard the implementation of both System level and Sub-System Level Solution.

One of the topics is the early S/C dismantlement by implementation of Platform Panels anticipated release.

This is a solution at Spacecraft level, that allows the access of the thermal flux to the most internal equipment.

The solutions envisaged foresee Shape Memory Alloys (SMA) or Eutectic materials I/Fs design that allow the release activated by Temperature at SC Re-entry.

Design of brackets, inserts, screws are strictly dependent on the specific Platform class selection (for the next COSMO SkyMed generations within PRIMA and Nimbus Platform Classes).

In specific cases (if necessary) this approach could be applied on supports of internal Equipment, in terms of material and design change.

This mainly applies to Spacecraft most internal items designed with high melting temperature materials.

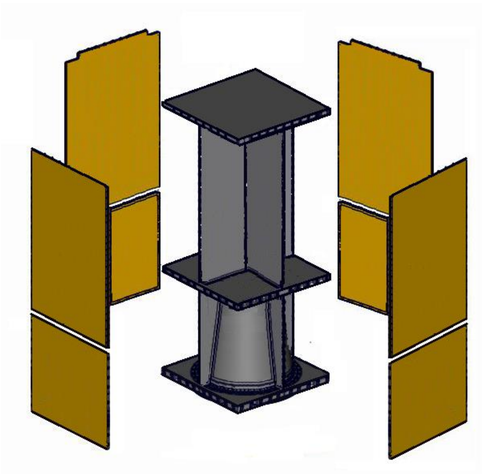

Figure 1. PRIMA Platform Potential Dismantlement Solution at EoL

Another System Level Improvement regards early release of external appendages activated by Temperature at SC Re-entry. Approach applicable for large appendices (e.g. antennas) that tipically shield the heat flux from some Platform surfaces, delaying the penetration inside the structure and therefore the demisability of the most critical internal items (e.g. Reaction Wheels, tank etc).

The possible solutions address Eutectic Solder or Shape Memory Alloys materials to join different parts of brackets. The materials are selected to have melting temperature and strength characteristic such that all mission loads (at nominal mission operating temperatures) are sustained.

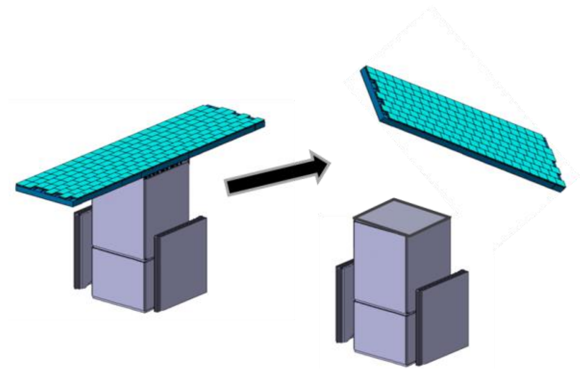

Figure 2. P/L vs PF Potential Detachment at EoL

Other Solutions at Sub-System Level have been identified as potential applications for COSMO-SkyMed Second Generation.

Actuators mainly composed of high melting temperature materials (such as Reaction Wheels, Magnetotorquers) are undergoing a process of re-design at European level with lower temperature melting materials (i.e. Aluminium instead of Iron). A preliminary design phase has been performed, and development is starting in the frame of GSTP.

Therefore these solutions still have a lower TRL and can be envisaged for future generations of COSMO-SkyMed depending on their availability on the Market.

Another Sub-System Level Solution regards the Tank design.

The Tank Ti-6Al-4V design and current configuration in COSMO-SkyMed Spacecraft (use of cone) leads to high contribution to Casualty Re-entry Risk.

Alternative technologies foresee different materials (metallic or thermoplastic/thermoset materials). They are in initial design phases (currently low TRL). Dedicated developments are currently planned at European Level.

The most promising technology for next COSMO-SkyMed generations relies on the use of metallic tanks compatible with N2H4.

Moreover compatibility with green propellant LMP-103S (already under assessment with this type of tanks at European level) would allow compliance with Reach normative and improve Propulsion performance.

The Propulsion S/S for green propellant will be designed taking into account the substitution of Hydrazine thrusters with green propellant thrusters (already available on European Market considering current COSMO-SkyMed Spacecraft nominal mission thrust needs).

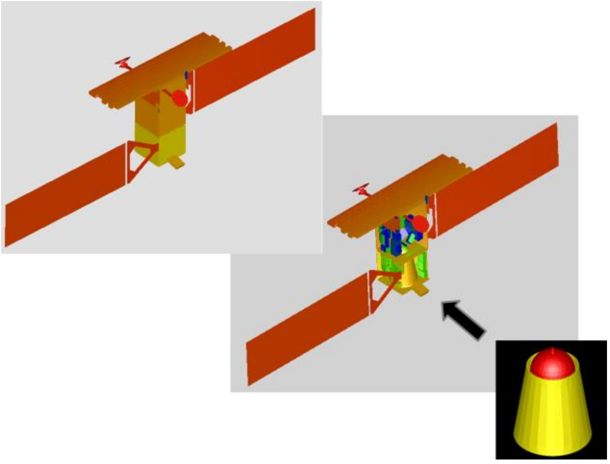

Figure 3. COSMO-SkyMed tank shielding

For uncontrolled re-entry also passivation topics are addressed.

Isolation of Solar Array in PCDU is aimed at minimising the risks of explosion after the EOL of a Spacecraft due to energy storage, by short-circuiting or open-circuiting all SA sections.

This passivation method is deemed the HW evolution of passivation already implemented on board for COSMO SkyMed of first and second generation, allowing reliability improvement, two step commands for safety, possibility of implementing a permanent or reversible approach.

The enabling technologies have extensive heritage (switches, relays), and the solution development starts from a high TRL. The possible architectures can be customised for the specific Programme, depending on applicable voltage and PCDU architecture (MPPT, S3R).

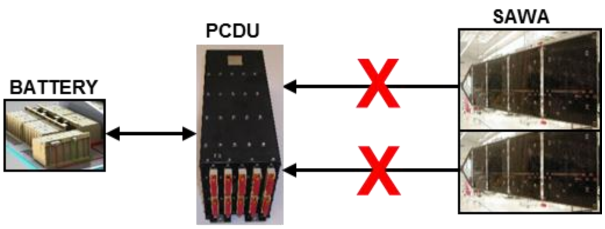

Figure 4. Electrical Power Sub-system Passivation (Solar Array Electrical Detachment from Battery)

2.2.2 Controlled Re-entry enabling technologies

The alternative to Design for Demise , in case of non-compliance to casualty re-entry risk , is to perform Controlled /semi-controlled re-entry, i.e. embarking enabling technologies able to allow a targeted re-entry on ground in a controlled manner.

Different solutions can be envisaged with different mission and SC design approches depending especially on the SC class and nominal orbit altitude.

For COSMO-SkyMed Spacecraft Class preliminary studies address possible improvement to on board thrusters, in terms of available thrust, and additional/enlarged tanks, maintaining the nominal features of propulsion system (i.e. chemical propulsion).

Other solutions mainly envisaged for smaller class Platforms could exploit electric propulsion S/S (e.g. arcjet , hall effect) for nominal mission and for lowering SC altitude at EOL, leaving the last thrust to a solid propulsion sub-system.

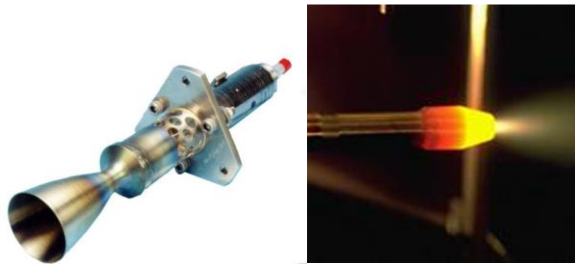

Figure 5. Examples of high thrust thrusters and arcjet thruster

Last but not least, beside improvements for Re-entry , another improvement regarding the Propulsion S/S is the potential use of green propellant.

This improvement would allow compliance to REACH Normative, and moreover the performance would be improved with respect to nominal hydrazine Sub-System.

For a whole sub-system compatibility with green propellant the nominal Ti-6Al-4V Tank can be used and already 1N thrusters are available in the European Market.

Obviously the potential application of concurrent design for demise and green propellant solutions would need further technologies:

- Demisable tank compatible with green propellant
- High thrust thruster for green propellant.

3 Conclusions

A summary table of the potential implementation of identified solutions in the frame of COSMO-SkyMed future Generations is reported below.

	Potential Applicability	
	COSMO-SkyMed Next Generation	COSMO-SkyMed Future Generations
Uncontrolled Re-entry		
Design for Demise		
System Level	⇧	⇧
Sub-System Level	⇩	⇧
Passivation	⇧	⇧
Controlled/Semi-Controlled Re-entry		
Chemical Propulsion		
N2H4	⇔	-
Green Propellant	⇩	⇧
Electric plus Solid Propulsion	⇩	⇧

Figure 6. Summary Table of Potential Application in COSMO-SkyMed next and future generations.

4 ABBREVIATIONS AND ACRONYMS

CSK COSMO-SkyMed

CSG COSMO-SkyMed Second Generation

TASI Thales Alenia Space Italy

SC Spacecraft

S/S Sub-System

AOCS Attitude and Orbit Control Sub-System

FMEA Failure Mode Effects Analysis

PNI Probability Of No Impact

LEO Low Earth Orbit

EOM End of Mission

EOL End of Life

SAW Solar Array Wings

PLM Platform Module

TRL Technology Readiness Level

SMA Shape Memory Alloy

GSTP General Support Technology Programme

PCDU Power Conversion and Distribution Unit

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