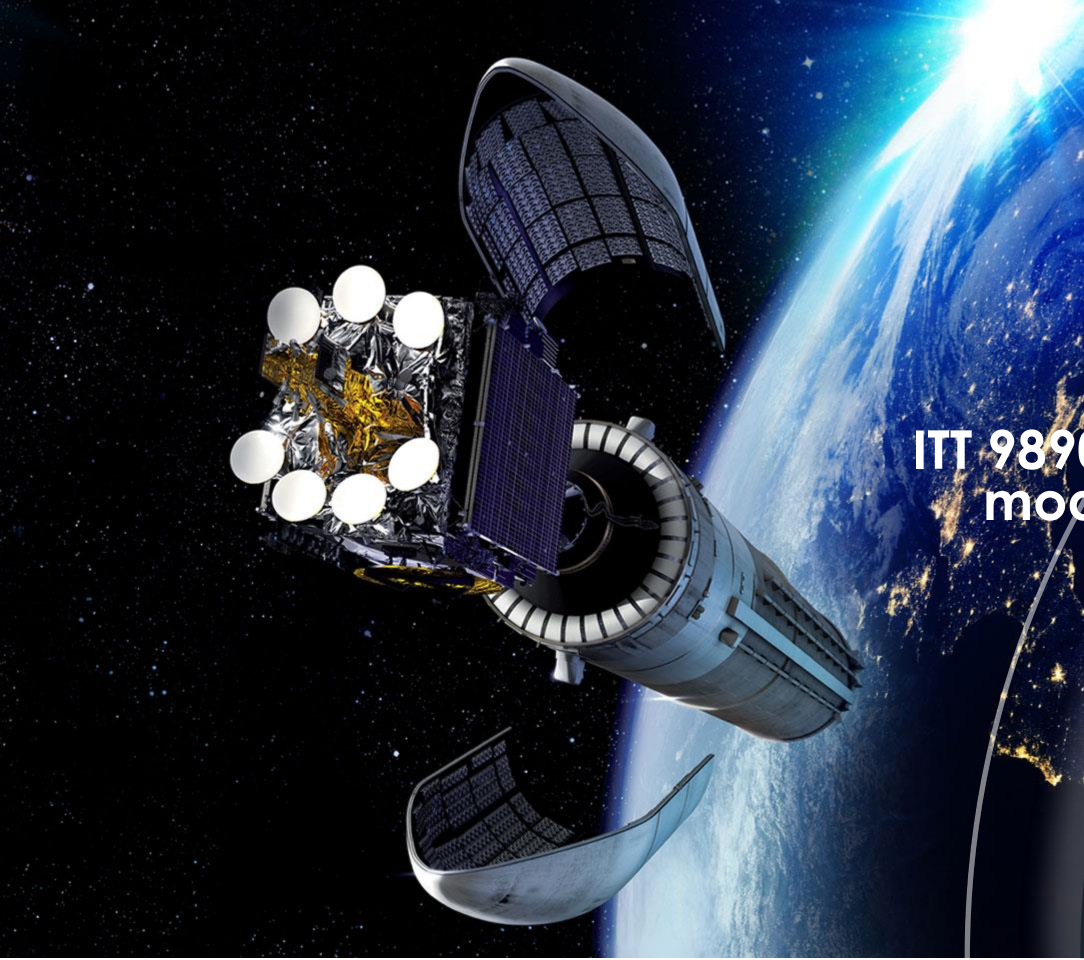


ITT 9890: Validated reliability based models for End of Life operations

Final review

04/11/2021

ThalesAlenia Space
a Thales / Leonardo company

Outline

Study management

- Team presentation
- Work logic
- Schedule
- Deliveries
- Payment plan

Introduction

- How to improve the satellite reliability and the success of the disposal ?
- Decision-making process on satellite End of Life

Study activities and results

- Reliability based estimates for EoL decision
- Risk assessment based estimates for EoL decision

Conclusions and way forwards

Study management

Team presentation

ESA

- **Fabrice Cosson – Silvana Radu**, Technical Officer
- **Ana Reinsoo**, Contract Officer

Thales Alenia Space - France

- **Lorenzo Bitetti**, Technical Officer & RAMS engineer
- **Emilien Genet**, RAMS engineer
- **Bernard Robert**, In Flight Customer Service engineer (MSG)
- **Christine Colas**, In-orbit support and Operation responsible
- **Sergio Di Girolamo**, TAS-F Contract Officer

Thales Alenia Space - Italy

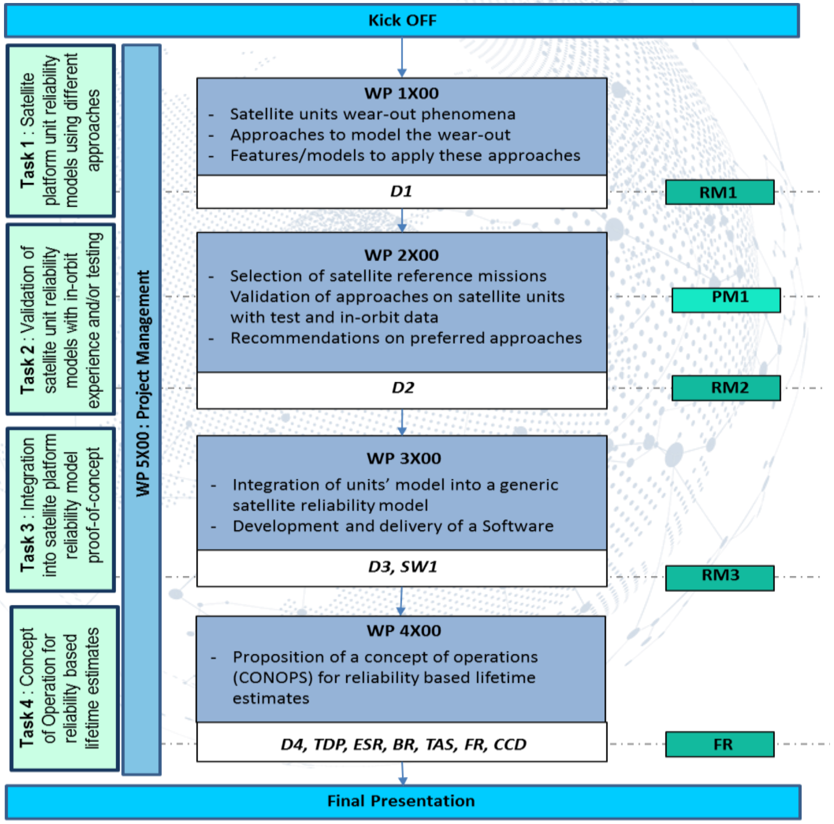
- **Beatrice Ratti**, TAS-I study manager / RAMS Expert
- **Federico Di Giandomenico**, RAMS engineer
- **Andrea Pirovano**, AOCS Space Operations Engineer
- **Roberto Destefanis**, **Francesca Tiboldo** Space Debris Expert
- **Laura Bufardeci**, TAS-I Contract Officer

Study management

Work logic

Four main phases have been defined :

- The **first task** :
  - to propose and develop reliability based lifetime models for satellite platform units exhibiting wear out
- The **second task** :
  - to validate the reliability models using test and/or in-orbit experience data
- The **third task** :
  - to integrate the unit level reliability models into a proof-of-concept of a whole satellite reliability model
- The **fourth task** :
  - to propose a concept of operations (CONOPS) for the application of reliability based lifetime estimates to satellite EoL operations



Kick OFF

Task 1 : Satellite platform unit reliability models using different approaches

Task 2 : Validation of satellite unit reliability models with in-orbit experience and/or testing

Task 3 : Integration into satellite platform reliability model proof-of-concept

Task 4 : Concept of Operation for reliability based lifetime estimates

WP 5X00 : Project Management

WP 1X00
- Satellite units wear-out phenomena
- Approaches to model the wear-out
- Features/models to apply these approaches

D1 — **RM1**

WP 2X00
- Selection of satellite reference missions
Validation of approaches on satellite units with test and in-orbit data
- Recommendations on preferred approaches

PM1

D2 — **RM2**

WP 3X00
- Integration of units' model into a generic satellite reliability model
- Development and delivery of a Software

D3, SW1 — **RM3**

WP 4X00
- Proposition of a concept of operations (CONOPS) for reliability based lifetime estimates

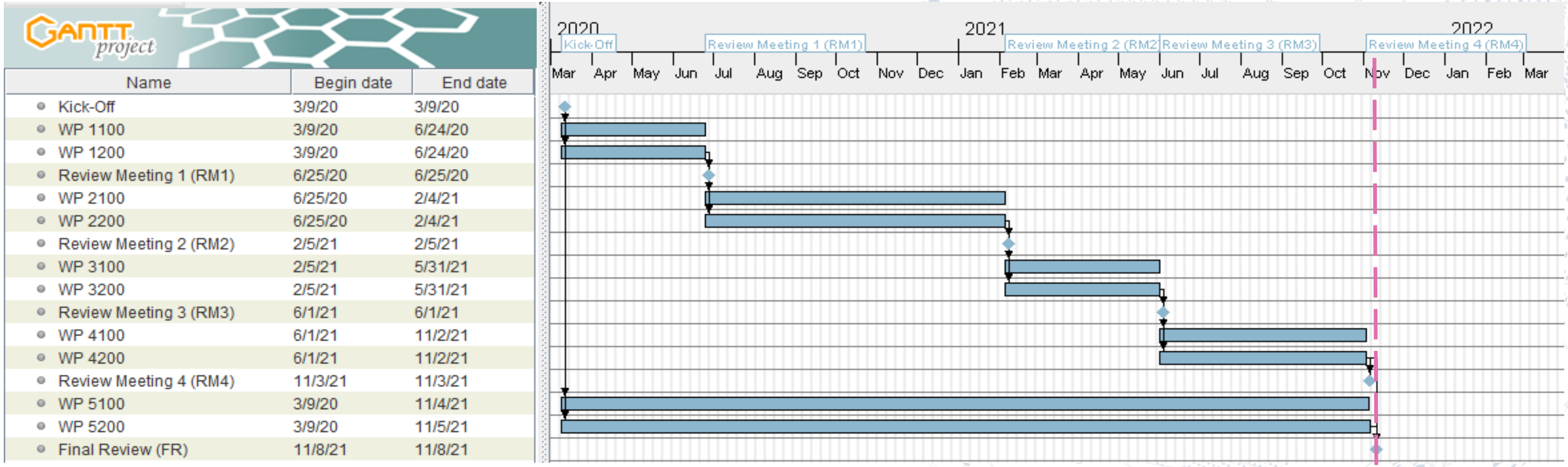
D4, TDP, ESR, BR, TAS, FR, CCD — **FR**

Final Presentation

Study management

Schedule

Overview of the study planning and reviews



Name	Begin date	End date
Kick-Off	3/9/20	3/9/20
WP 1100	3/9/20	6/24/20
WP 1200	3/9/20	6/24/20
Review Meeting 1 (RM1)	6/25/20	6/25/20
WP 2100	6/25/20	2/4/21
WP 2200	6/25/20	2/4/21
Review Meeting 2 (RM2)	2/5/21	2/5/21
WP 3100	2/5/21	5/31/21
WP 3200	2/5/21	5/31/21
Review Meeting 3 (RM3)	6/1/21	6/1/21
WP 4100	6/1/21	11/2/21
WP 4200	6/1/21	11/2/21
Review Meeting 4 (RM4)	11/3/21	11/3/21
WP 5100	3/9/20	11/4/21
WP 5200	3/9/20	11/5/21
Final Review (FR)	11/8/21	11/8/21

The project has been globally on schedule. Only few months of delay wrt initial planning, despite Covid situation.

Study management

Deliveries

Doc. Id	Title	Meeting	Format
D1	TN1 : Satellite platform unit reliability models using stochastic, model-based, and/or data trend analyses	RM#1	Word + PDF
D2	TN2 : Validation of satellite platform unit reliability models	RM#2	Word + PDF
D3	TN3 : Satellite platform reliability model proof-of-concept	RM#3	Word + PDF
D4	TN4 : CONOPS and preliminary requirements for reliability driven design, health monitoring and operations	RM#4	Word + PDF
TDP	Technical Data Package	Final Review	Word + PDF
ESR	Executive Summary Report	Final Review	Word + PDF
FR	Final Presentation	Final Review	PowerPoint file
BR	Brochure	Final Review	Website Article Template
TAS	Technology Achievement Summary	Final Review	Technology Achievement template
FR	Final Report	Contract Closure	Word + PDF
CCD	Contract Closure Documentation	Contract Closure	Signed electronic copy

Remaining documents will be sent as soon as D4 is reviewed and accepted.

SW Id	Title	Milestone	Format
[SW1]	Software model (*)	RM#3	1 electronic copy to be agreed (**)

(*) empty template and MSG specific model
(**) both open and confidential Excel version delivered

Study management

Technical note 4 contents and structure

TN 4 : CONOPS and preliminary requirements for reliability driven design, health monitoring and operations

- 3 INTRODUCTION TO APPROACHES FOR EOL DECISION
  - 3.1 Before the introduction of SDM requirements – Past approach
  - 3.2 After the introduction of SDM requirements – Current approach
    - ***3.2.1 Examples of decision making process for EoL***
    - ***3.2.2 Focus on RAMS aspects***
    - ***3.2.3 Focus on MMOD probability and impact on EoL disposal***
  - 3.3 Future and ideal approach for EoL decision
- 4 CONCEPT OF OPERATIONS FOR BETTER RISK-AWARENESS DECISIONS ON EOL
  - 4.1 CONOPS for the Consumable criterion
  - 4.2 CONOPS for Reliability based lifetime estimates
  - 4.3 CONOPS for Risk Assessment estimates
- 5 Conclusions

Study planning

Payment plan

Payment plan as per Contract

Milestone (MS) Description	schedule date	Payment
Progress (MS 1): Upon successful completion of Review Meeting at the end of Task 1 (RM1) and the Agency's acceptance of all related deliverables	T0 + 3 m	140 000 €
Progress (MS 2): Upon successful completion of Review Meeting at the end of Task 2 (RM2) and the Agency's acceptance of all related deliverables	T0 + 9 m	110 000 €
Progress (MS 3): Upon successful completion of Review Meeting at the end of Task 3 (RM3) and the Agency's acceptance of all related deliverables	T0 + 12 m	80 000 €
Final (MS 4): Upon the Agency's acceptance of all delivery items due under the Contract and the Contractor fulfilment of all other contractual obligations including submission of the signed Contract Closure Documentation.	T0 + 16 m	70 000 €
	400 000 €	

Last invoice to be sent once MS4 is considered as successful by ESA and remaining documents delivered

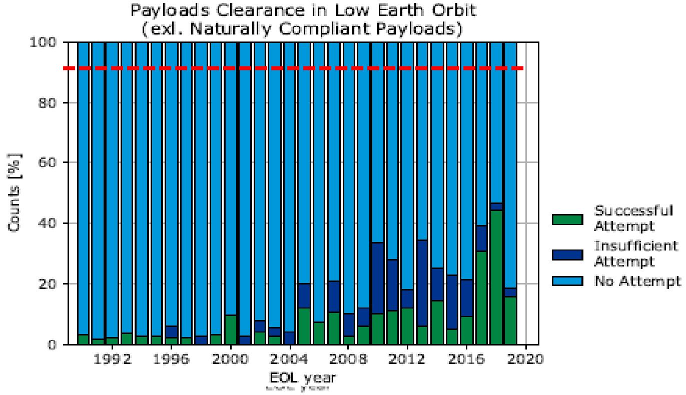
TN4
§1

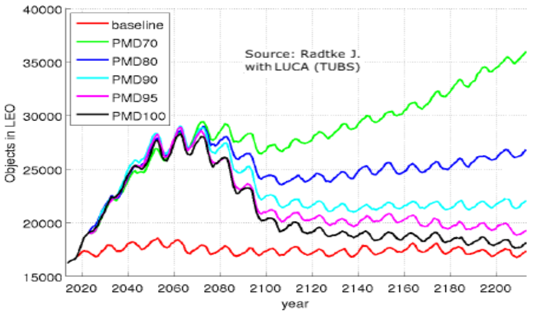
Introduction

Background

- The success rate of the End of Life disposal currently observed in LEO is well below the 90% required in international SDM standards !
- It is even lower if satellites naturally compliant with the 25-year rule are not considered in the statistics !
- Success rate is higher in GEO, mainly because of the telecom operators interest in guaranteeing the sustainability of ‘limited orbit slots’ in the GEO arc
- The population of space debris in LEO is expected to grow :
  - because of satellites left in orbit or lost after the occurrence of failures
  - Because of eventual collisions or explosions in orbit
  - and especially because of future large constellations
- A high Post Mission Disposal success rate will be needed in the near future to stabilize the evolution of the space debris population

Some improvements are needed in order to be able to dispose the satellite in a reliable manner and especially at the right time !





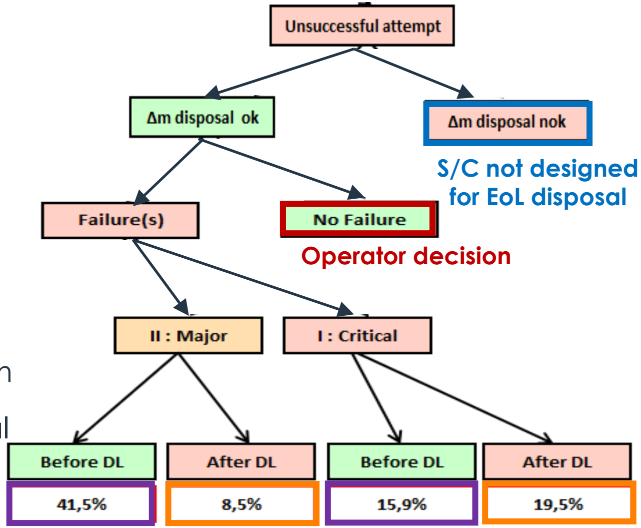
Source: Radtke J. with LUCA (TUBS)

TN4
§3.2.2

How to improve the satellite reliability and the success of the disposal ?

Analysis of root causes and potential solutions

- Main reasons for unsuccessful EoL disposal
  - Old satellites not designed for EoL disposal (ex. not enough propellant mass)
  - Recommendations and not regulations → not really an obligation
  - Wrong or too late decision on the disposal initiation :
    - decision mainly based on consumables (e.g. propellant mass) but less on the risk of losing the disposal capability because of already occurred failures or possible future ones
- Analysis of root causes repartition done by Thales Alenia Space starting from SpaceTrack and CeleStrak databases for about 100 LEO satellites naturally not compliant to the 25-year rule that have not succeeded the EoL disposal
  - Enough propellant mass at least for ‘best effort’ deorbit in almost all cases
  - Some cases of operator decision not to perform the disposal (13.5%)
  - Several cases of satellites experiencing major or critical failures (85.5%)
    - mostly occurred during the Design Lifetime (DL) of the satellite (57.5%)
    - but also during an already extended missions (28%)
- Current/future S/C have to be designed for the EoL disposal and operators are no longer allowed to deliberately decide not to deorbit their S/C
- **But how to avoid that failures would lead to an unsuccessful disposal in the future?**



Unsuccessful attempt

Δm disposal ok

Δm disposal nok

S/C not designed for EoL disposal

Failure(s)

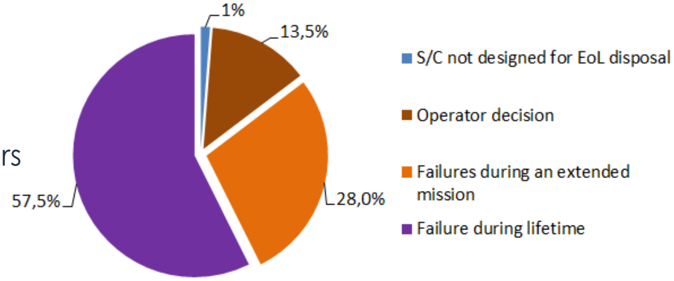
No Failure

Operator decision

II : Major

I : Critical

Before DL	After DL	Before DL	After DL
41,5%	8,5%	15,9%	19,5%

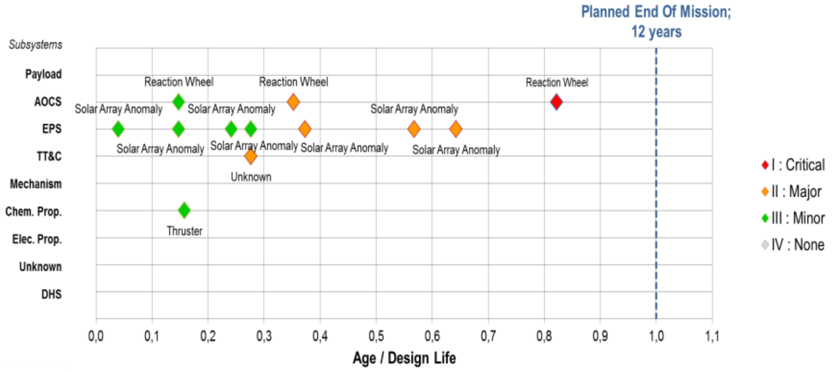


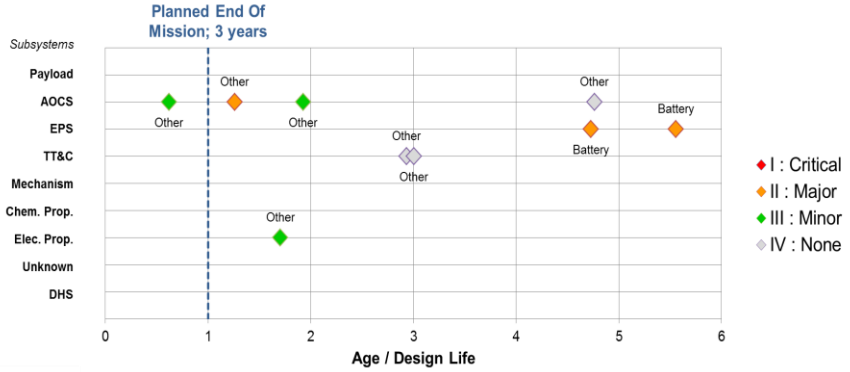
TN4
§3.2.2

How to improve the satellite reliability and the success of the disposal ?

Analysis of root causes and potential solutions

- Examples of failure scenarios leading to an unsuccessful disposal in the past (GEO and LEO satellites)





Don't you think that these satellite could/should have been disposed before their complete lost ?

even if the GEO S/C hadn't achieved yet its nominal lifetime ?

especially because the LEO S/C was already well beyond its nominal lifetime?

How and when a decision to deorbit could/should have been taken ?

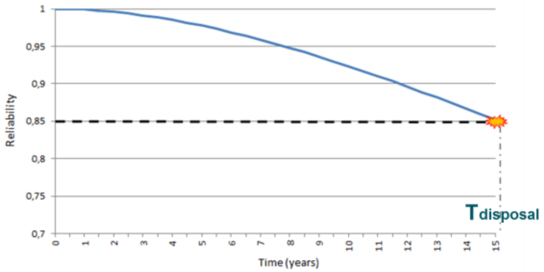
TN4
§3.2.2

How to improve the satellite reliability and the success of the disposal ?

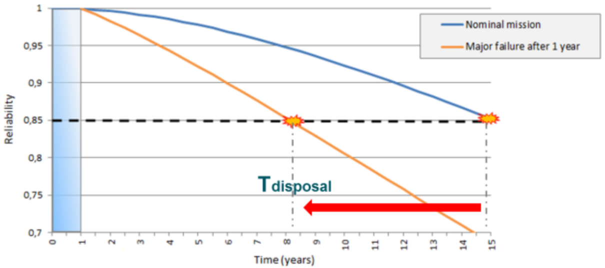
How RAMS engineers can contribute to the improvement of the decision-making process ?

> " ***Specific criteria for initiating the disposal of a spacecraft shall be developed, evaluated during the mission and, if met, consequent actions executed.*** " (ISO 24113 standard, Ed.3, July 2019)

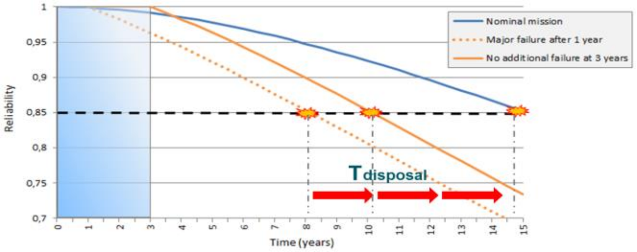
- Remaining propellant mass criterion
- Requirement on disposal probability
  - Currently the 0.85 (LOS) or 0.9 (ISO) is used as reliability decision criterion during the mission
  - **But this requirement does not constitute an adequate criterion to decide for a disposal !**



In case of failure after a given time



But… if recomputed later on during the mission



Disposal manoeuvers can be always delayed and, even worse, never started !

A SPF satellite would be still compliant and thus authorized to stay in orbit for few years !

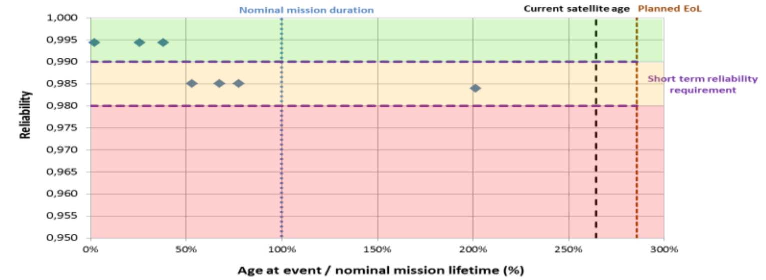
In addition, initial CDR model is not (always) accurate and representative of real PMD reliability !

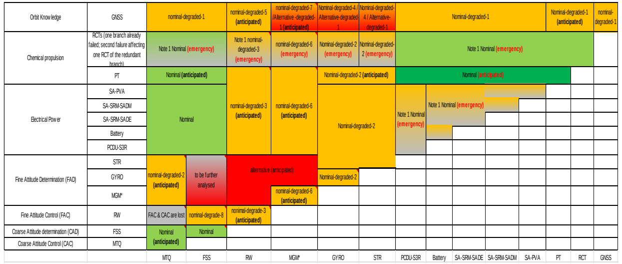
TN4
§3.3

How to improve the satellite reliability and the success of the disposal ?

Proposed improvements for the decision making process

- Two solutions have been proposed and evaluated:
  - **Short-term reliability criterion (Quantitative)**
    - Reference duration and reliability thresholds selected to distinguish different scenarios: **nominal**, **warning** and **critical**
    - Disposal recommended when the reliability reassessed during the mission is lower than a given threshold
  - **Risk assessment approach (Qualitative)**
    - To derive the risk of losing the disposal capability after any combination of two major failures
    - To show their impact on the disposal strategy and timeframe
    - To provide stakeholders a clear picture of potential risks
    - Disposal recommended when there is a high risk of loosing the disposal capability





Orbit Knowledge	GNSS	nominal-degraded-1		nominal-degraded-5 **(anticipated)**	nominal-degraded-7 /Alternative -degraded-1 **(anticipated)**	Nominal-degraded-4 / Alternative-degraded-1	Nominal-degraded-4 / Alternative-degraded-1	Nominal-degraded-1					Nominal-degraded-1 **(anticipated)**		nominal-degraded-1
Chemical propulsion	RCTs (one branch already failed; second failure affecting one RCT of the redundant branch)	Note 1 Nominal (emergency)		Note 1 nominal-degraded-3 (emergency)	nominal-degraded-6 (emergency)	Nominal-degraded-2 (emergency)	Nominal-degraded-2 (emergency)	Note 1 Nominal (emergency)							
	PT	Nominal **(anticipated)**		nominal-degraded-3 **(anticipated)**	nominal-degraded-6 **(anticipated)**	Nominal-degraded-2 **(anticipated)**		Nominal (anticipated)							
Electrical Power	SA-PVA	Nominal				Nominal-degraded-2		Note 1 Nominal (emergency)	Note 1 Nominal (emergency)						
	SA-SRM-SADM														
	SA-SRM-SADE														
	Battery														
	PCDU-S3R														
Fine Attitude Determination (FAD)	STR	nominal-degraded-2 **(anticipated)**	to be further analysed	alternative (anticipated)											
	GYRO					Nominal-degraded-2									
	MGM*				nominal-degraded-6 **(anticipated)**										
Fine Attitude Control (FAC)	RW	FAC & CAC are lost	nominal-degrade-8	nonimal-degrade-3 **(anticipated)**											
Coarse Attitude determination (CAD)	FSS	Nominal **(anticipated)**	Nominal												
Coarse Attitude Control (CAC)	MTQ														
		MTQ	FSS	RW	MGM*	GYRO	STR	PCDU-S3R	Battery	SA-SRM-SADE	SA-SRM-SADM	SA-PVA	PT	RCT	GNSS

- Final goal :
  - to define suitable criteria to support EoL decision and to recommend the start of the manoeuvers before completely losing the disposal capability

TN4
§3.3

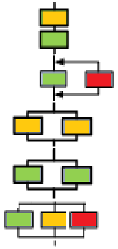
Decision-making process on satellites End of Life

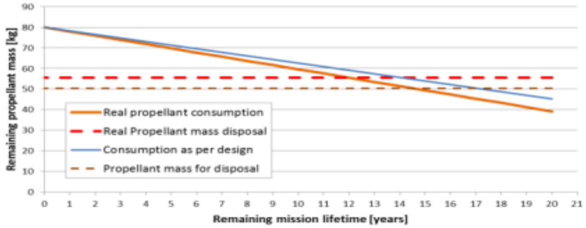
Overview of the approach and its operational application

The disposal criteria will be monitored during the whole mission and appropriate actions will have to be taken in case the thresholds are reached.

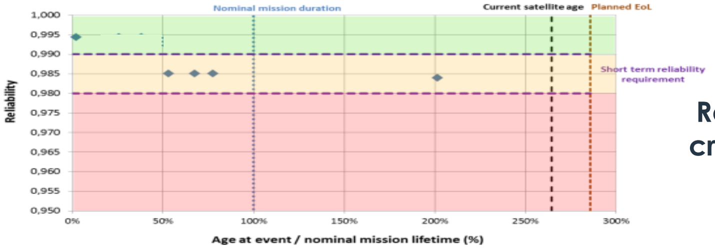
During the mission ….

S/System	Equipment	Unit	Current status
Subsystem 1	Hardware 1	HW 1.1	Limited lifetime
		HW 1.2	OK
	Hardware 2	HW 2 Primary	OK
		HW 2 Redundant	Failed
	Hardware 3	HW 3.1	Limited lifetime
		HW 3.2	Limited lifetime
Subsystem 2	Hardware 4	HW 4.1	OK
		HW 4.2	OK
	Hardware 5	HW 5.1	OK
		HW 5.2	Limited lifetime
		HW 5.3	Failed

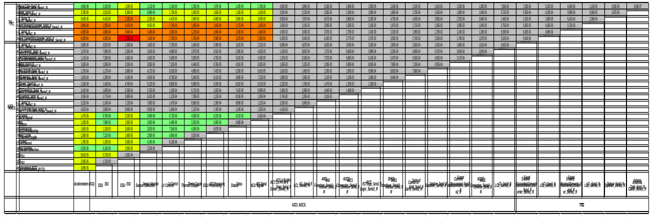




Consumable criterion



Reliability criterion



Risk assessment

These quantitative and qualitative approaches would lead to a better risk-awarded decision on the EoL and thus to a higher PMD success rate in orbit !

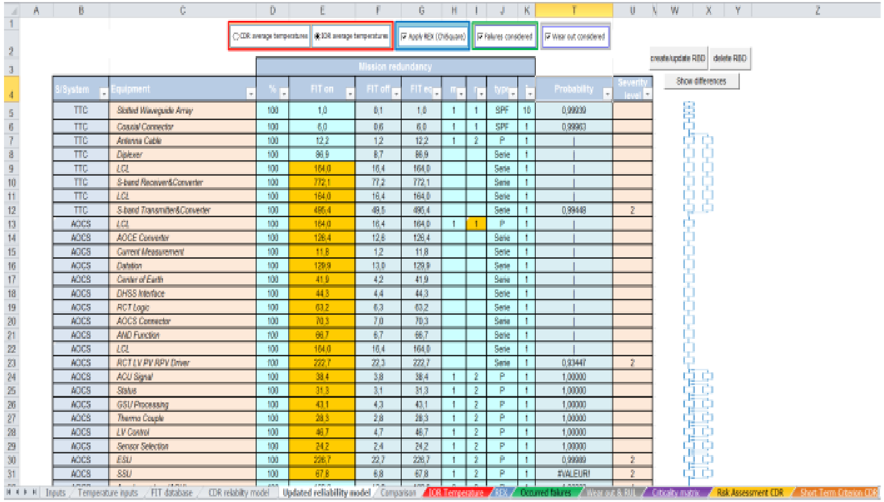
TN3
§5

Decision-making process on satellites End of Life

Overview of the proof-of-concept of RAMS tool supporting EoL decision

A proof-of-concept of an Excel tool has been developed in order to correctly and accurately re-assess the reliability figures during the mission:

- Approach 1: With updated RBD after the occurrence of failures
- Approach 2: With real operating conditions (ex. temperature) wrt CDR assumptions
- Approach 2: With the integration of REX (Chi² method, Bayesian techniques)
- Approach 3: With the modeling of wear out of units and Remaining Useful Lifetime (RUL)
  - Constant failure rate but different from the initial one
  - Weibull law (Pseudo failure time method)
  - Bertholon law = Exponential + Weibull
  - Mortality law (lognormal) from unit RUL
  - Probabilistic model (Erfc function) from unit RUL
- Other approaches: To generate and update the risk assessment matrix



○ CDR average temperatures ● IOR average temperatures ☑ Apply REX (ChiSquare) ☑ Failures considered ☑ Wear out considered

		Mission redundancy									
S/System	Equipment	%	FIT on	FIT off	FIT eq	m	n	type		Probability	Severity level
TTC	Slotted Waveguide Array	100	1,0	0,1	1,0	1	1	SPF	10	0,99939	
TTC	Coaxial Connector	100	6,0	0,6	6,0	1	1	SPF	1	0,99963	
TTC	Antenna Cable	100	12,2	1,2	12,2	1	2	P	1		
TTC	Diplexer	100	86,9	8,7	86,9			Serie	1		
TTC	LCL	100	164,0	16,4	164,0			Serie	1		
TTC	S-band Receiver&Converter	100	772,1	77,2	772,1			Serie	1		
TTC	LCL	100	164,0	16,4	164,0			Serie	1		
TTC	S-band Transmitter&Converter	100	496,4	49,5	496,4			Serie	1	0,99448	2
AOCS	LCL	100	164,0	16,4	164,0	1	1	P	1		
AOCS	AOCE Converter	100	128,4	12,8	128,4			Serie	1		
AOCS	Current Measurement	100	11,8	1,2	11,8			Serie	1		
AOCS	Datation	100	129,9	13,0	129,9			Serie	1		
AOCS	Center of Earth	100	41,9	4,2	41,9			Serie	1		
AOCS	DHSS Interface	100	44,3	4,4	44,3			Serie	1		
AOCS	RCT Logic	100	63,2	6,3	63,2			Serie	1		
AOCS	AOCS Connector	100	70,3	7,0	70,3			Serie	1		
AOCS	AND Function	100	66,7	6,7	66,7			Serie	1		
AOCS	LCL	100	164,0	16,4	164,0			Serie	1		
AOCS	RCT LV PV RPV Driver	100	222,7	22,3	222,7			Serie	1	0,93447	2
AOCS	ACU Signal	100	38,4	3,8	38,4	1	2	P	1	1,00000	
AOCS	Status	100	31,3	3,1	31,3	1	2	P	1	1,00000	
AOCS	GSU Processing	100	43,1	4,3	43,1	1	2	P	1	1,00000	
AOCS	Thermo Couple	100	28,3	2,8	28,3	1	2	P	1	1,00000	
AOCS	LV Control	100	46,7	4,7	46,7	1	2	P	1	1,00000	
AOCS	Sensor Selection	100	24,2	2,4	24,2	1	2	P	1	1,00000	
AOCS	ESU	100	226,7	22,7	226,7	1	2	P	1	0,99989	2
AOCS	SSU	100	67,8	6,8	67,8	1	2	P	1	#VALEUR!	2

This tool allows to easily follow the qualitative and quantitative RAMS criteria supporting EoL decision making process

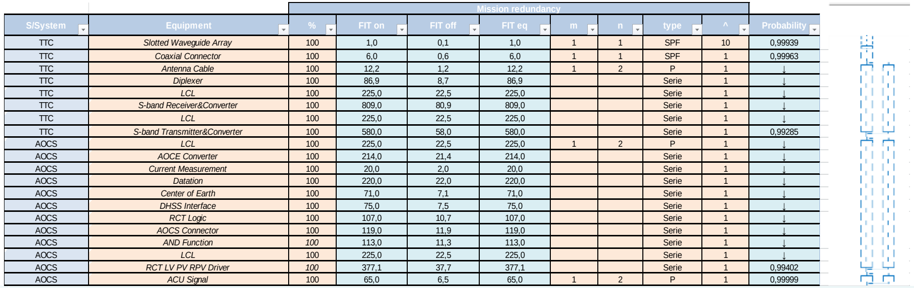
TN3
§3.2

Reliability based estimates

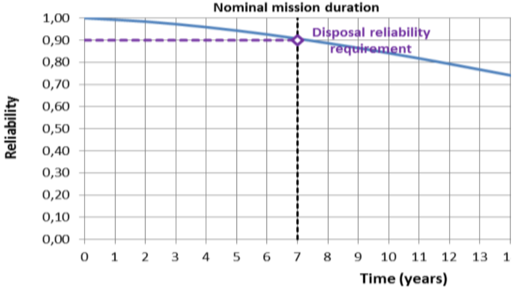
Approach 0: Initial (CDR) model

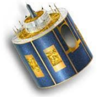
- Objective
  - To demonstrate the compliance with the SDM requirement before launch
- Inputs
  - EoL disposal strategy (functionalities and units) and classical reliability data (*under engineering and RAMS responsibility*)
- Methods / tools
  - As per a classical reliability analysis (*under RAMS responsibility*)
- Outputs
  - Evolution over time of the EoL probability and compliance with SDM requirement (*under RAMS responsibility)*
- Comments & Recommendations
  - Not enough accurate for the purpose of reassessment during the mission

'CDR reliability model' sheet



		Mission redundancy								
S/System	Equipment	%	FIT on	FIT off	FIT eq	m	n	type	^	Probability
TTC	*Slotted Waveguide Array*	100	1,0	0,1	1,0	1	1	SPF	10	0,99939
TTC	*Coaxial Connector*	100	6,0	0,6	6,0	1	1	SPF	1	0,99963
TTC	*Antenna Cable*	100	12,2	1,2	12,2	1	2	P	1	↓
TTC	*Diplexer*	100	86,9	8,7	86,9			Serie	1	↓
TTC	*LCL*	100	225,0	22,5	225,0			Serie	1	↓
TTC	*S-band Receiver&Converter*	100	809,0	80,9	809,0			Serie	1	↓
TTC	*LCL*	100	225,0	22,5	225,0			Serie	1	↓
TTC	*S-band Transmitter&Converter*	100	580,0	58,0	580,0			Serie	1	0,99285
AOCS	*LCL*	100	225,0	22,5	225,0	1	2	P	1	↓
AOCS	*AOCE Converter*	100	214,0	21,4	214,0			Serie	1	↓
AOCS	*Current Measurement*	100	20,0	2,0	20,0			Serie	1	↓
AOCS	*Datation*	100	220,0	22,0	220,0			Serie	1	↓
AOCS	*Center of Earth*	100	71,0	7,1	71,0			Serie	1	↓
AOCS	*DHSS Interface*	100	75,0	7,5	75,0			Serie	1	↓
AOCS	*RCT Logic*	100	107,0	10,7	107,0			Serie	1	↓
AOCS	*AOCS Connector*	100	119,0	11,9	119,0			Serie	1	↓
AOCS	*AND Function*	*100*	113,0	11,3	113,0			Serie	1	↓
AOCS	*LCL*	100	225,0	22,5	225,0			Serie	1	↓
AOCS	*RCT LV PV RPV Driver*	*100*	377,1	37,7	377,1			Serie	1	0,99402
AOCS	*ACU Signal*	100	65,0	6,5	65,0	1	2	P	1	0,99999





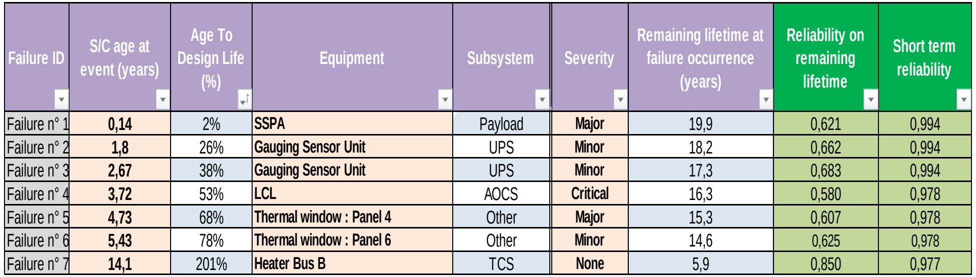
TN4 §4.2.1.1
TN3 §3.3

Reliability based estimates

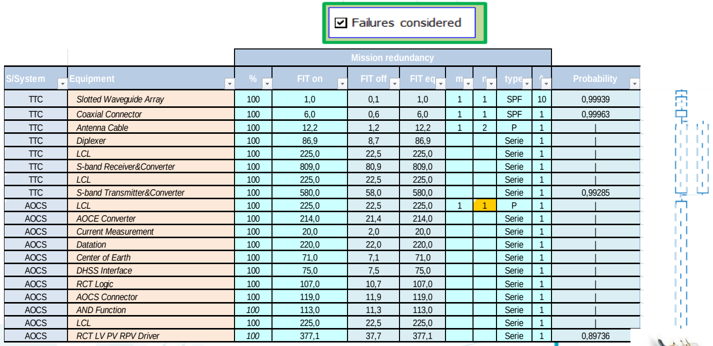
Approach 1: occurred failures

- Objective
  - To update the CDR model with the failures occurred during the mission and the corresponding operational changes
- Inputs
  - At least, the information on the failed units and time of failure (*underline operators responsibility*)
- Methods / tools
  - Manual / automatic update of the initial reliability model (*under RAMS responsibility*)
- Outputs
  - Updated number of available units and any other modification linked to the new operational context and the reconfiguration strategy (ex. unit ON/OFF, cold/hot redundancy, duty cycle) (*under RAMS responsibility)*
- Comments & Recommendations
  - Better than 0 but still not enough accurate for the purpose of reassessment during the mission

‘**Occurred failures**’ **sheet**

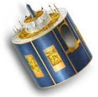


Failure ID	S/C age at event (years)	Age To Design Life (%)	Equipment	Subsystem	Severity	Remaining lifetime at failure occurrence (years)	Reliability on remaining lifetime	Short term reliability
Failure n° 1	0,14	2%	SSPA	Payload	Major	19,9	0,621	0,994
Failure n° 2	1,8	26%	Gauging Sensor Unit	UPS	Minor	18,2	0,662	0,994
Failure n° 3	2,67	38%	Gauging Sensor Unit	UPS	Minor	17,3	0,683	0,994
Failure n° 4	3,72	53%	LCL	AOCS	Critical	16,3	0,580	0,978
Failure n° 5	4,73	68%	Thermal window : Panel 4	Other	Major	15,3	0,607	0,978
Failure n° 6	5,43	78%	Thermal window : Panel 6	Other	Minor	14,6	0,625	0,978
Failure n° 7	14,1	201%	Heater Bus B	TCS	None	5,9	0,850	0,977



☑ Failures considered

S/System	Equipment	Mission redundancy %	FIT on	FIT off	FIT eq	m	n	type	^	Probability
TTC	*Slotted Waveguide Array*	100	1,0	0,1	1,0	1	1	SPF	10	0,99939
TTC	*Coaxial Connector*	100	6,0	0,6	6,0	1	1	SPF	1	0,99963
TTC	*Antenna Cable*	100	12,2	1,2	12,2	1	2	P	1	|
TTC	*Diplexer*	100	86,9	8,7	86,9			Serie	1	|
TTC	*LCL*	100	225,0	22,5	225,0			Serie	1	|
TTC	*S-band Receiver&Converter*	100	809,0	80,9	809,0			Serie	1	|
TTC	*LCL*	100	225,0	22,5	225,0			Serie	1	|
TTC	*S-band Transmitter&Converter*	100	580,0	58,0	580,0			Serie	1	0,99285
AOCS	*LCL*	100	225,0	22,5	225,0	1	1	P	1	|
AOCS	*AOCE Converter*	100	214,0	21,4	214,0			Serie	1	|
AOCS	*Current Measurement*	100	20,0	2,0	20,0			Serie	1	|
AOCS	*Datation*	100	220,0	22,0	220,0			Serie	1	|
AOCS	*Center of Earth*	100	71,0	7,1	71,0			Serie	1	|
AOCS	*DHSS Interface*	100	75,0	7,5	75,0			Serie	1	|
AOCS	*RCT Logic*	100	107,0	10,7	107,0			Serie	1	|
AOCS	*AOCS Connector*	100	119,0	11,9	119,0			Serie	1	|
AOCS	*AND Function*	*100*	113,0	11,3	113,0			Serie	1	|
AOCS	*LCL*	100	225,0	22,5	225,0			Serie	1	|
AOCS	*RCT LV PV RPV Driver*	*100*	377,1	37,7	377,1			Serie	1	0,89736

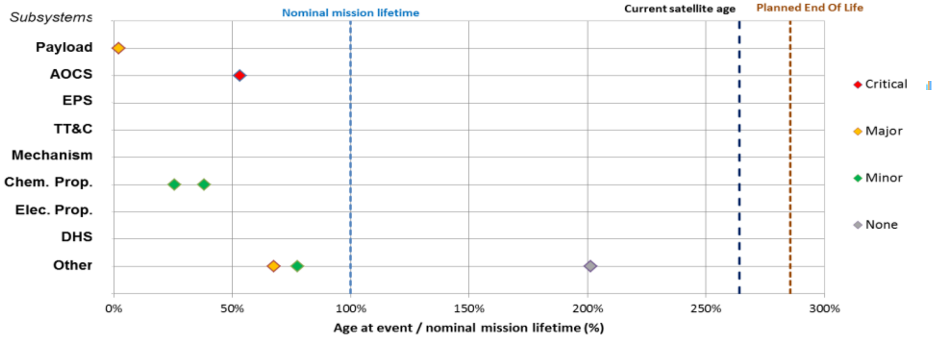


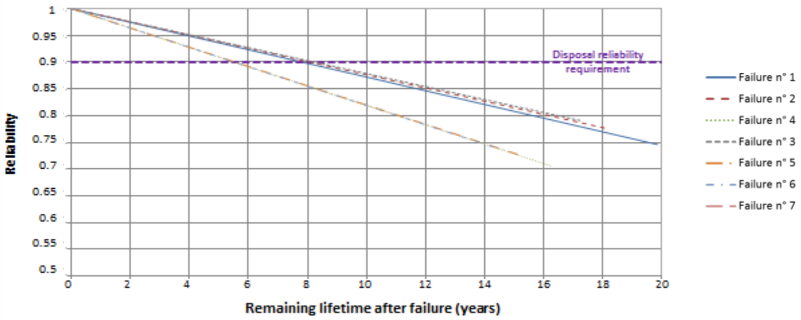
TN3
§4.1.3.1

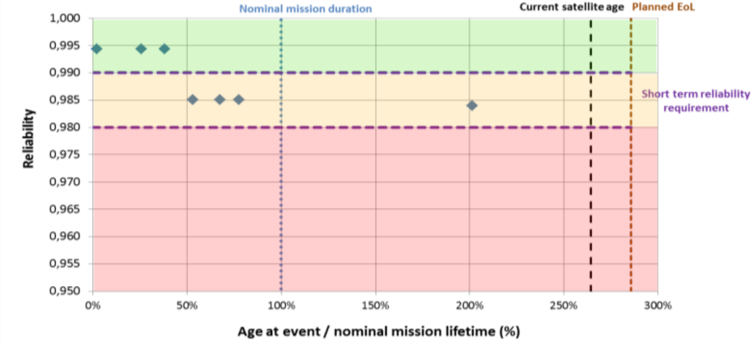
Reliability based estimates

Approach 1: occurred failures

‘Occurred failures’ sheet - Example







Reassessing the compliance with 0.9 PMD success rate is not an appropriate decision criterion for EoL !

Reliability criterion thought to be more useful for a better risk-awareness decision on EoL

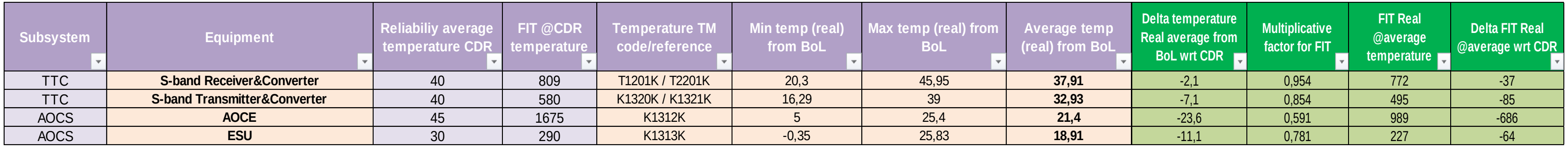
TN4 §4.2.1.2
TN3 §3.4

Reliability based estimates

Approach 2: Health monitoring – real operating temperature

- Objective
  - To update and to better evaluate the unit failure rate by taking into account real operating conditions
- Inputs
  - failure rates at different temperatures (*under RAMS responsibility*) - ideally at least 3 values
  - In Orbit Return temperatures (*under operators responsibility*)
- Methods / tools
  - Different approaches possible: FIT at min/max/average T°, integration of FIT, … (*under RAMS responsibility*)
  - Operational tools for gathering, formatting and providing IOR TMs
- Outputs
  - units' failure rate updated with the IOR temperature instead of CDR assumption (*under RAMS responsibility)*
- Comments & Recommendations
  - More accurate and usually less pessimistic reliability figures.
  - Priority to high T° and high FIT HW. Not applicable to all units (ex. mechanical, REX)

'IOR temperature' sheet

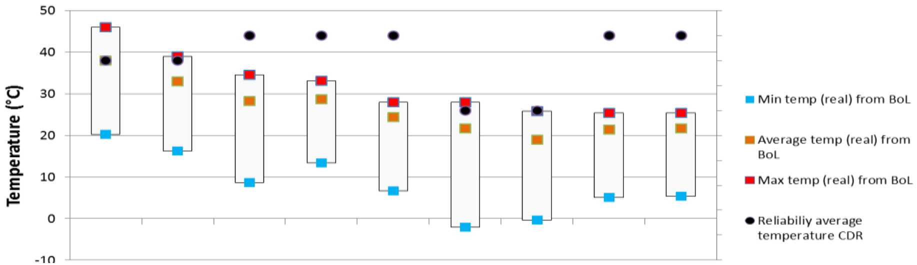


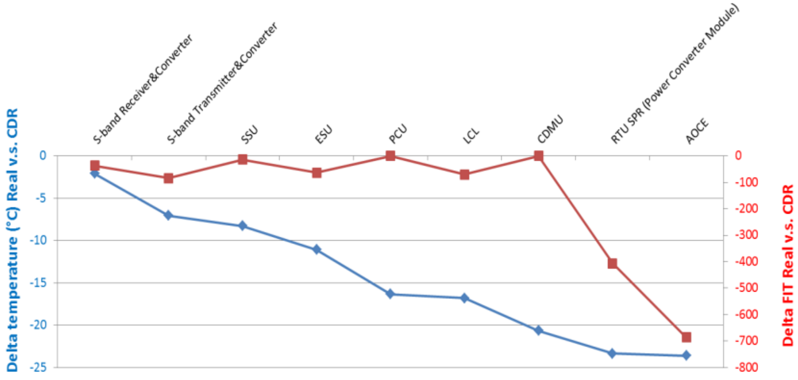
Subsystem	Equipment	Reliabiliy average temperature CDR	FIT @CDR temperature	Temperature TM code/reference	Min temp (real) from BoL	Max temp (real) from BoL	Average temp (real) from BoL	Delta temperature Real average from BoL wrt CDR	Multiplicative factor for FIT	FIT Real @average temperature	Delta FIT Real @average wrt CDR
TTC	**S-band Receiver&Converter**	40	809	T1201K / T2201K	20,3	45,95	**37,91**	-2,1	0,954	772	-37
TTC	**S-band Transmitter&Converter**	40	580	K1320K / K1321K	16,29	39	**32,93**	-7,1	0,854	495	-85
AOCS	**AOCE**	45	1675	K1312K	5	25,4	**21,4**	-23,6	0,591	989	-686
AOCS	**ESU**	30	290	K1313K	-0,35	25,83	**18,91**	-11,1	0,781	227	-64

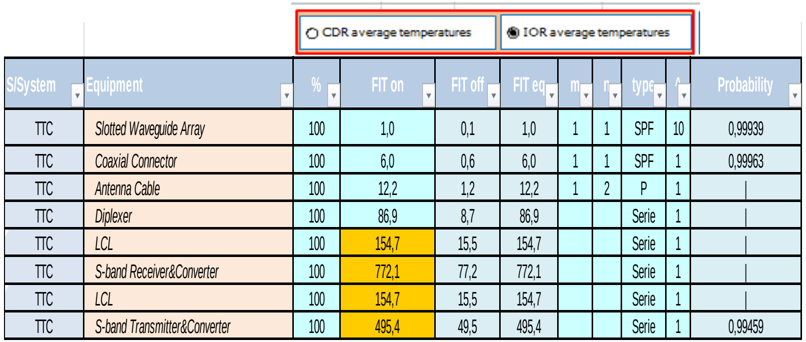
Reliability based estimates

Approach 2: Health monitoring – real operating temperature

‘**IOR temperature**’ sheet - Example

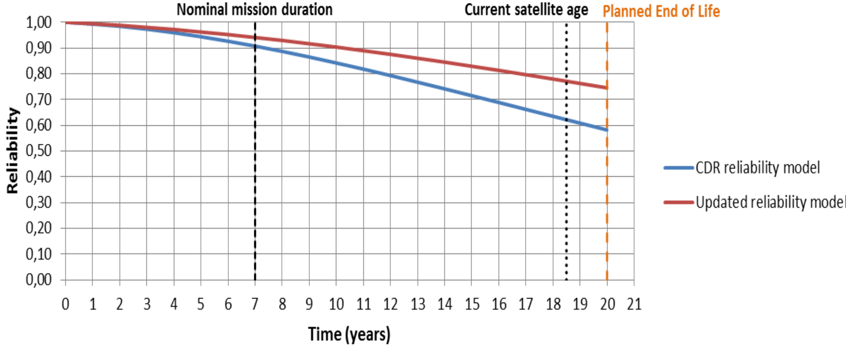






○ CDR average temperatures ● IOR average temperatures

S/System	Equipment	%	FIT on	FIT off	FIT eq	m	r	type		Probability
TTC	Slotted Waveguide Array	100	1,0	0,1	1,0	1	1	SPF	10	0,99939
TTC	Coaxial Connector	100	6,0	0,6	6,0	1	1	SPF	1	0,99963
TTC	Antenna Cable	100	12,2	1,2	12,2	1	2	P	1	|
TTC	Diplexer	100	86,9	8,7	86,9			Serie	1	|
TTC	LCL	100	154,7	15,5	154,7			Serie	1	|
TTC	S-band Receiver&Converter	100	772,1	77,2	772,1			Serie	1	|
TTC	LCL	100	154,7	15,5	154,7			Serie	1	|
TTC	S-band Transmitter&Converter	100	495,4	49,5	495,4			Serie	1	0,99459



Usually the initial CDR model is quite conservative

A more accurate assessment could be useful for the EoL decision

TN4 §4.2.1.3

Reliability based estimates

Approach 2: Health monitoring – units performance and margins

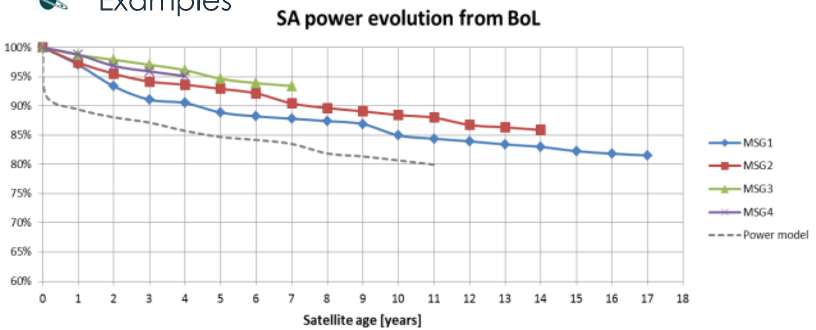
- Objective
  - To monitor the performance of the unit in order to identify any symptom of anomaly, failure or performance degradation.
- Inputs
  - Observables depending on the unit under analyses (*under operators responsibility, with support of unit expert*)
- Methods / tools
  - As per current In Flight Services activities with Operator specific tools (stakeholders as above)
- Outputs
  - Updated redundancy schemes (e.g. more or less failures accepted) depending on existing margins (*RAMS responsibility*)
  - Non nominal behavior can be identified and the unit recovered before the occurrence of failure
- Comments & Recommendations
  - Some parameters are not always monitored and/or available.
  - Health monitoring needed also for the prognostic approaches.

TN2 §4.1.2
TN2 §4.2.2

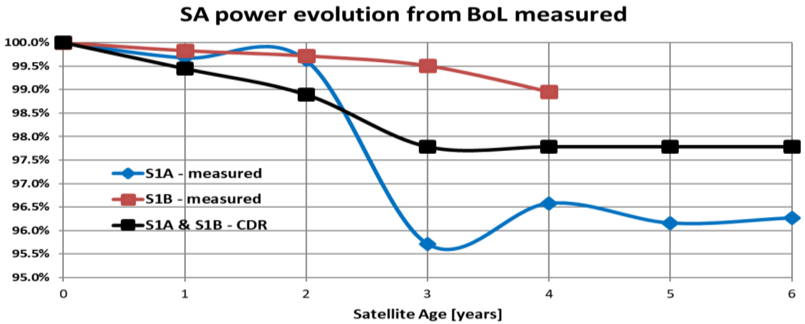
Reliability based estimates

Approach 2: Health monitoring – units performance and margins

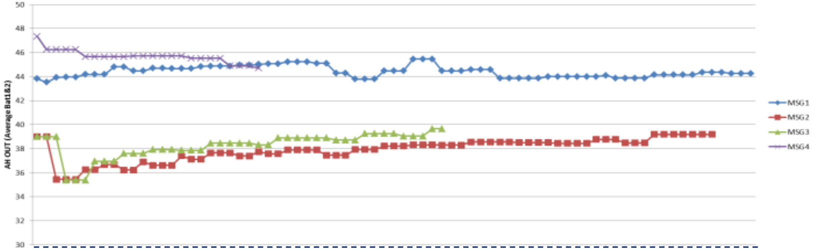
Examples



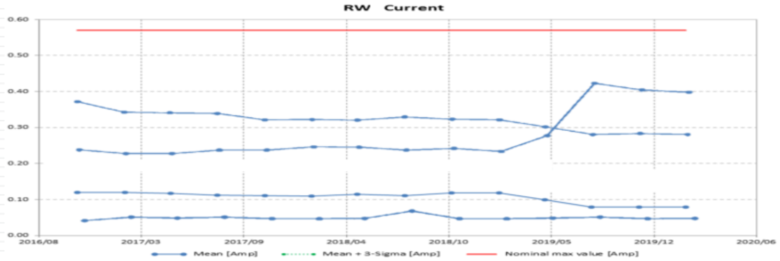
Decrease of solar array power lower than the expected one → higher margins and tolerance to much more than 1 string loss



Decrease of solar array power on S1A after MMOD impact. Anyway still positive power budget because of eng. margins



Overall good behavior and performance of the battery well above mission needs → high confidence for life extension



Overall good and stable behavior of the RW, performance below 'failure' threshold

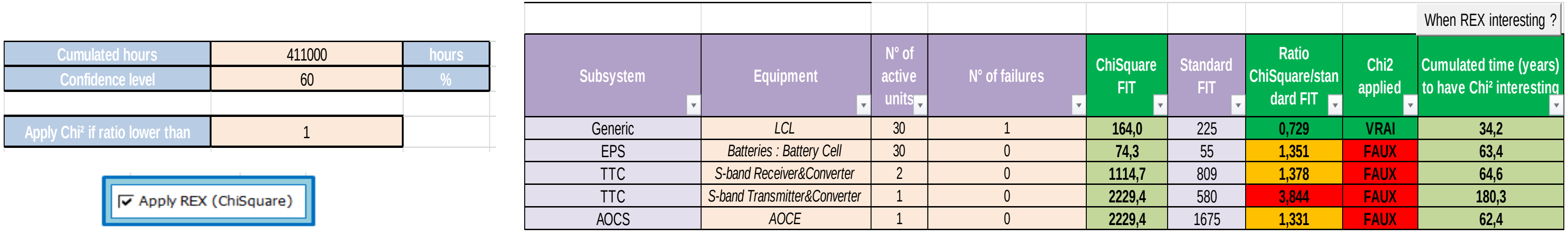
TN4 §4.2.1.4
TN3 §3.5

Reliability based estimates

Approach 2: Return of experience – Chi Square method & Bayesian techniques

- Objective
  - To compute the failure rate of one unit from the return of experience
- Inputs
  - Number of failures, if any, occurred during cumulated working hours (*<u>under operators responsibility</u>*)
- Methods / tools
  - Chi Square method & Bayesian techniques (*<u>under RAMS responsibility, ideally at supplier level</u>*)
- Outputs
  - Reliability model taking into account the failure rate derived from the REX (*<u>under RAMS responsibility</u>*)
- Comments & Recommendations
  - A large amount of cumulated hours needed to come up with an ‘interesting’ failure rate
  - Incorrect/risky approach for those units experiencing wear out phenomena

‘REX’ sheet

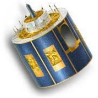


Cumulated hours	411000	hours
Confidence level	60	%
Apply Chi^2 if ratio lower than	1	

☑ Apply REX (ChiSquare)

When REX interesting ?

Subsystem	Equipment	N° of active units	N° of failures	ChiSquare FIT	Standard FIT	Ratio ChiSquare/standard FIT	Chi2 applied	Cumulated time (years) to have Chi^2 interesting
Generic	*LCL*	30	1	164,0	225	0,729	VRAI	34,2
EPS	*Batteries : Battery Cell*	30	0	74,3	55	1,351	FAUX	63,4
TTC	*S-band Receiver&Converter*	2	0	1114,7	809	1,378	FAUX	64,6
TTC	*S-band Transmitter&Converter*	1	0	2229,4	580	3,844	FAUX	180,3
AOCS	*AOCE*	1	0	2229,4	1675	1,331	FAUX	62,4

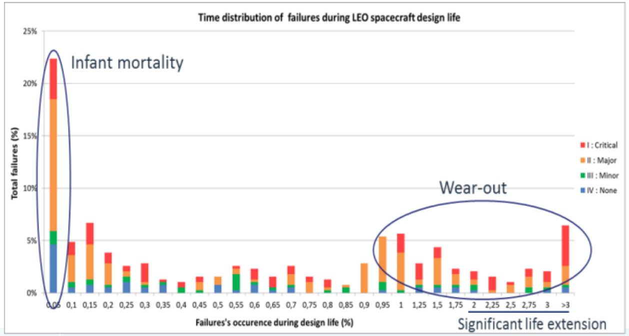


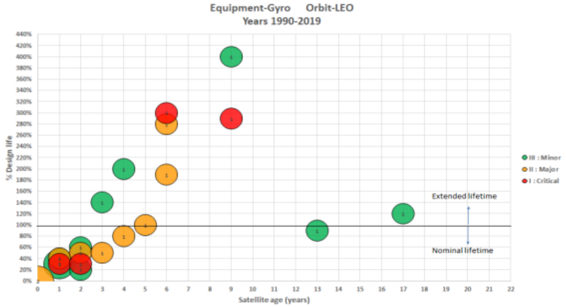
TN4 §4.2.1.4
TN2 §4.1.3.2

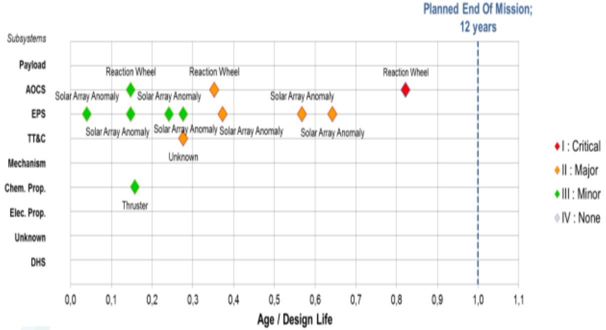
Reliability based estimates

Approach 2: Return of experience – Statistics on occurred failures

- Objective
  - To better understand the anomalies and failures encountered in orbit
- Inputs
  - Database of anomalies/failures occurred in orbit : internal and/or public database
- Methods / tools
  - Statistics on occurrence, severity, time distribution, failure history, … (*under RAMS responsibility)*
- Outputs
  - To identify the really risky/severe failures and/or those occurred more or less frequently in orbit
  - To identify those units experiencing infant mortality and/or wear out effects, thus needing a more complex model
  - To consolidate and reinforce a recommendation on EoL in order to avoid being in a failure scenario that has already lead to the loss of the satellite in the past







TN4 §4.2.1.5
TN3 §3.6

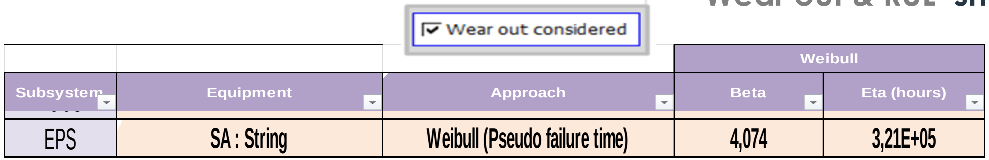
Reliability based estimates

Approach 3a: Prognostic based on stochastic models

- Objective
  - To predict at any time the future status of the units and estimate their Remaining Useful Lifetime (RUL)
- Inputs
  - In-orbit data - health monitoring *(under operators responsibility)*
  - Threshold for the maximum degradation and Remaining Useful Lifetime (supplier or expert-advised information)
- Methods / tools
  - Constant failure rate but different from the initial one
  - Weibull law (Pseudo failure time method)
  - Bertholon law = Exponential + Weibull
  - Mortality law (lognormal) from unit RUL
  - Probabilistic model (Erfc function) from unit RUL

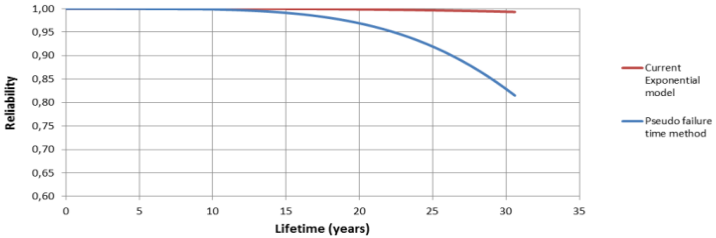
  (under RAMS responsibility)
- Outputs
  - Reliability model taking into account unit wear out, RUL and/or survival probability *(under RAMS responsibility)*
- Comments & Recommendations
  - Preferable, when applicable, to exploit real data to correctly estimate the parameters of the law instead of engineering judgment

'Wear out & RUL' sheet



☑ Wear out considered

			Weibull	
Subsystem	Equipment	Approach	Beta	Eta (hours)
EPS	SA : String	Weibull (Pseudo failure time)	4,074	3,21E+05



TN4 §4.2.1.6
TN4 §4.2.1.7

Reliability based estimates

Approach 3b/c: Prognostic based on engineering models / data trend analysis

- Objective
  - As per Approach 3a
- Inputs
  - As per Approach 3a
  - Performance/degradation engineering models for 3b (under supplier or unit expert responsibility)
  - Training and In-orbit data for 3c
- Methods / tools
  - Engineering models for 3b (under supplier or unit expert responsibility)
  - Specific machine learning methods and Data Trend Analysis tools for 3c (under data trend expert responsibility)
- Outputs
  - Reliability model taking into account unit wear out, RUL and/or survival probability (*under RAMS responsibility)*
- Comments & Recommendations
  - Performance/degradation models are available only for few satellite units
  - Access to proprietary tools is sometimes limited. Thus prime manufacturer and/or unit supplier need to be involved
  - Accuracy of the models, especially if used outside the nominal/qualified behavior, to be carefully assessed and justified
  - Even if not evaluated in depth, Approach 3c is seen as a very promising

TN1 §5.6.1.3
TN2 §4.1.7

Reliability based estimates

Other approaches : Prognostic based on radiation drifts

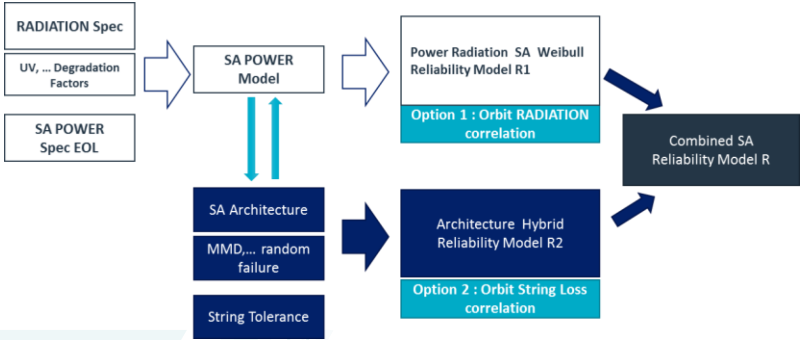
- Objective
  - To determine the maximum achievable lifetime of EEE units linked to total radiation dose
- Inputs
  - Initial radiation analysis
  - Initial Worst Case analysis (under Radiation and unit designer responsibility)
  - Observed / estimated radiation dose cumulated during the mission
- Methods / tools
  - Derived from Radiation Design Margin (under Radiation expert responsibility)
  - Derived from Worst Case Analysis (under unit designer responsibility)
- Outputs
  - Reliability model taking into account the RUL of EEE units linked to radiation dose (*under RAMS responsibility)*
- Comments & Recommendations
  - First method already performed in the past on some specific units (platform or payload)
  - Even if not easy, this approach is highly recommended for very extended missions
  - On board radiation monitoring ideally needed
- Example
  - SIRAL Altimeter: design dose of 10 Krad
  - TIDL dose of 1.7 krad @5.6 years in orbit, equivalent to 0.304 Krad / year,
  - Leading to a predicted radiation lifetime of about 32.9 years → 27 years+ of RUL

TN1 §3.5.2
TN2 §4.1.8

Reliability based estimates

Other approaches : Reliability synthetic approach for mechanical units

- Objective
  - To better estimate the reliability of mechanical units
- Inputs
  - Unit design and sizing margins
  - Failure mechanism analysis
  - Radiation and MMOD estimations
  - In orbit return
- Methods / tools
  - Combined method as per NRPM : Physic of Failure + Statistics
- Outputs
  - More accurate reliability model for mechanical / electro-mechanical units *(under RAMS responsibility)*
- Comments & Recommendations
  - Interesting both for the design phase and prognostic
  - Usually mechanical units have a low contribution to probability but this approach could be very interesting for some units
- Example
  - Solar Array combined method including radiation and MMOD effects in addition to classical string tolerance
  - Correlation with in orbit performance
  - Prognostic on future performance



RADIATION Spec
UV, ... Degradation Factors
SA POWER Spec EOL
SA POWER Model
Power Radiation SA Weibull Reliability Model R1
Option 1 : Orbit RADIATION correlation
SA Architecture
MMD,... random failure
String Tolerance
Architecture Hybrid Reliability Model R2
Option 2 : Orbit String Loss correlation
Combined SA Reliability Model R

TN4
§4.3

Risk assessment estimates

Overview

In addition to 'classical' risk analyses

- List of Critical SPF
- list of items known to experience wear out and/or 'consumed' during the mission
- list of Operation Life limited Items (OLI)
- Fault Tree Analysis (FTA)
- Probabilistic Risk Assessment (PRA)

Other analyses and decision criteria have been proposed

- Double failure matrix
- Enhanced Risk Assessment

TN4 §4.3.1
TN3 §3.8

Risk assessment estimates

Double failure matrix

- Objective
  - Before launch: to highlight critical scenarios → to improve the design and to anticipate alternative solutions
  - During the mission: to identify any new critical case and to support EoL decision
- Inputs
  - As per a classical FMEA analysis
- Methods / tools
  - As per a classical FMEA but considering each combination of two failures for those units required for the EoL
- Outputs
  - Matrix where the impacts on the mission and the corresponding corrective/compensatory means are shown
    - Still possible to follow a **nominal EoL strategy**?
    - EoL possible only with a **contingency** or **emergency** strategy?
    - **Loss of the complete EoL disposal capability** ?
  - Evaluation of the probability
    - Of being in such a critical situation over the (remaining) mission
    - Of being able to succeed the disposal in a short timeframe if the scenario arise
- Comments & Recommendations
  - provide a clear picture of the current and future risk of keeping the satellite in orbit
  - graphical representation of the outcomes which can be understood also by non RAMS experts

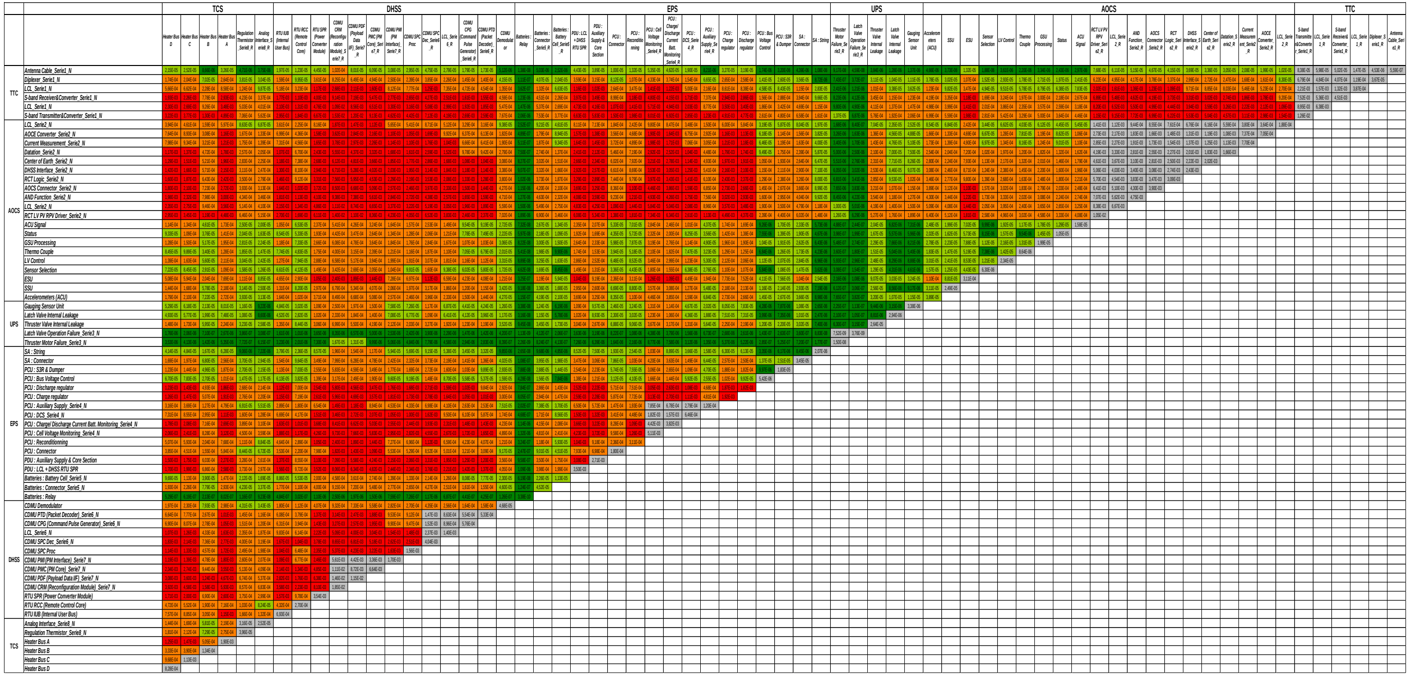
TN3
§4.1.5

Risk assessment estimates

Double failure matrix

- Example

Double failure matrix before launch



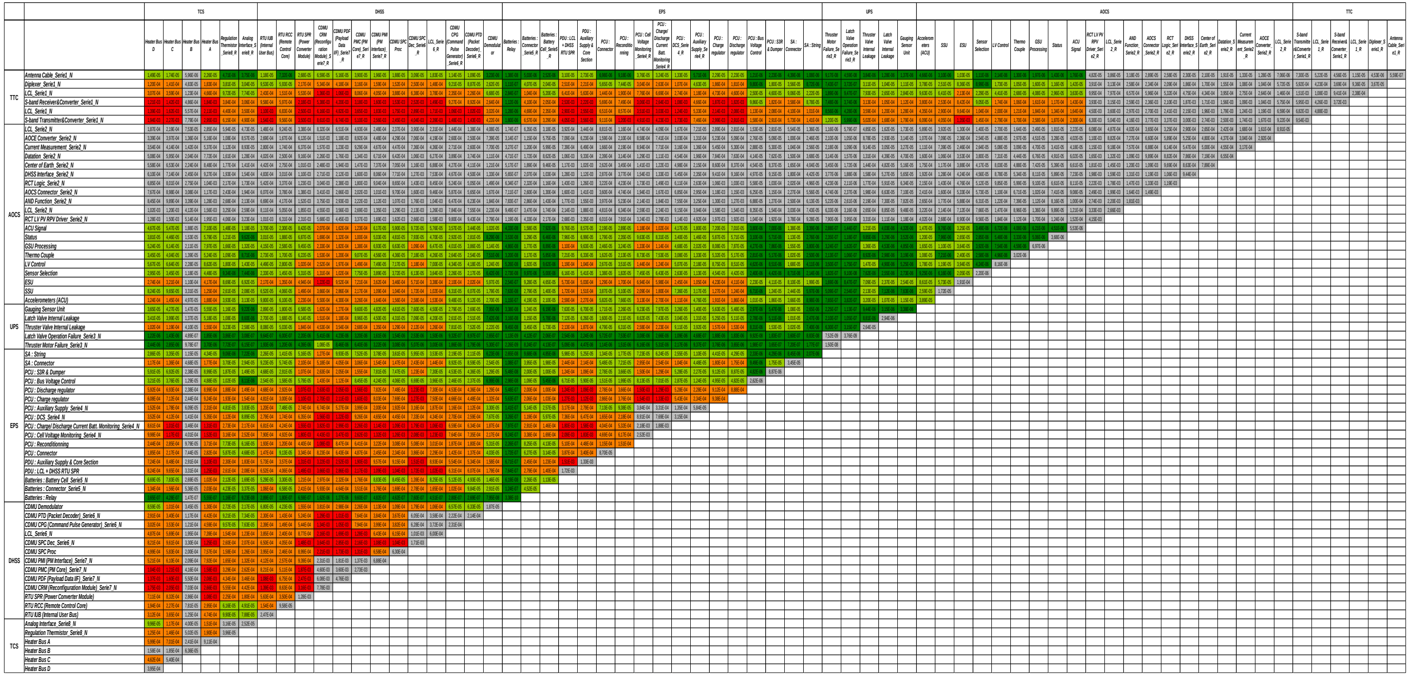
TN3
§4.1.5

Risk assessment estimates

Double failure matrix

- Example

Double failure matrix <u>updated during the mission</u>



TN4
§4.3.2

Risk assessment estimates

Enhanced Risk Assessment

- Objective
  - Before launch: to highlight critical scenarios → to improve the design and to anticipate alternative solutions.
  - During the mission: to assess the Loss of Disposal risk evolution in time and to provide criteria for decision-making on extending the satellite life or initiating the disposal of the spacecraft.
- Inputs
  - Disposal strategy, in-orbit failures, equipment in-orbit temperature, equipment RUL, satellite FMEA.
- Methods / tools
  - Development of a FTA dedicated to the feared event "Loss of disposal capability" accounting for the disposal strategy, in-orbit failures, equipment in-orbit temperature, equipment RUL, satellite FMEA. All possible equipment failure combinations (i.e. Cut Sets) that can lead to the Loss of Disposal are generated. Disposal/no-disposal criteria are defined (e.g. Risk Index = Prob Nb x Sev Num, PSuccDisp, PDegrDisp,…) and the thresholds are revised together with the satellite owner/customer/operator.
- Outputs
  - The Enhanced Risk Assessment Technique can automatically provide several output data. Among others:
    - Number and percentage of cut sets wrt SN-PN matrix
    - Number of cut sets vs RI (Risk Index)
    - Cut sets with a RI>x (for any "x" value)
    - Failed items list
    - Probability of disposal loss
    - Probability of disposal loss using degraded strategy…
- Comments & Recommendations
  - A multi-disciplinary Enhanced Risk Assessment Technique can be developed and implemented on single satellites and/or constellations to support decision-making process for extending in-orbit mission.
  - The technique is suitable for applications in the whole satellite life, and in particular at the end of nominal mission duration, representing the starting point for the risk assessment evolution. In addition, it can be used also at any point in time of the satellite nominal life in case of faults/anomalies that change the satellite configuration, expected life or operation.

TN4
§4.3.2

Risk assessment estimates

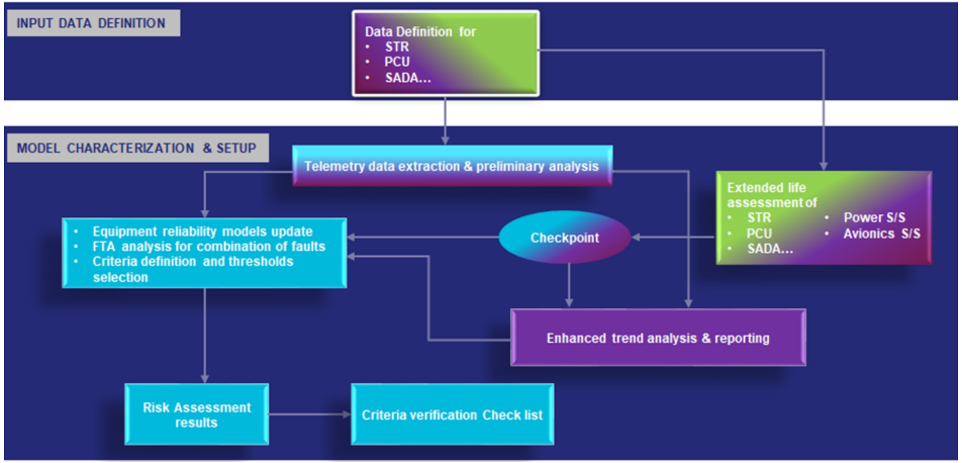
Enhanced Risk Assessment

Working logic

Streams of activity / stakeholders / data

Equipment life extension assessments (*)	Enhanced Trend Analysis & Platform assessments	Enhanced Risk Assessment technique
STR life extension assessment	Enhanced Trend analysis & Reporting: increase the set of analyzed TMs and improve techniques	Telemetry data extraction & preliminary analysis
SADA life extension assessment	Avionics subsystem analysis	Equipment reliability models update from in-orbit data trends
PCU life extension assessment	Power subsystem analysis	FTA/FMEA analysis for combinations of faults
Gyro life extension assessment….	Life extension assessment of equipment for which unit supplier input is not available	Risk assessment for combinations of faults & criteria verification
⬇ Equip. life extension assessment TNs	⬇ Enhanced Trend Analysis TN	⬇ Enhanced Risk Assessment TN

Processes / methods / interactions



INPUT DATA DEFINITION

Data Definition for
- STR
- PCU
- SADA…

MODEL CHARACTERIZATION & SETUP

Telemetry data extraction & preliminary analysis

Extended life assessment of
- STR
- PCU
- SADA…
- Power S/S
- Avionics S/S

- Equipment reliability models update
- FTA analysis for combination of faults
- Criteria definition and thresholds selection

Checkpoint

Enhanced trend analysis & reporting

Risk Assessment results

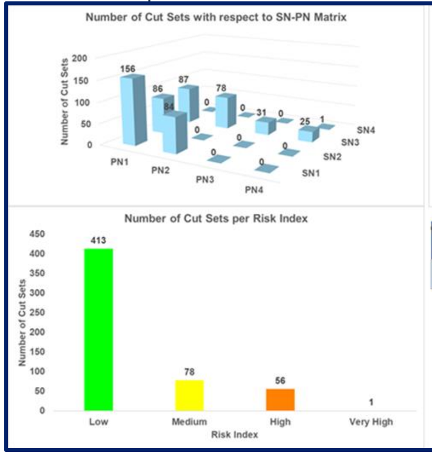
Criteria verification Check list

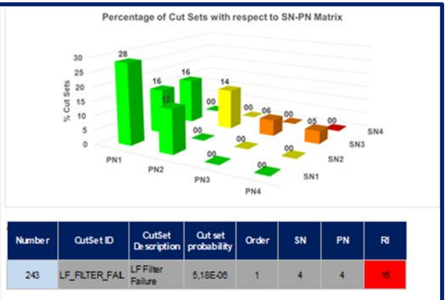
TN4
§4.3.2

Risk assessment estimates

Enhanced Risk Assessment

- Example

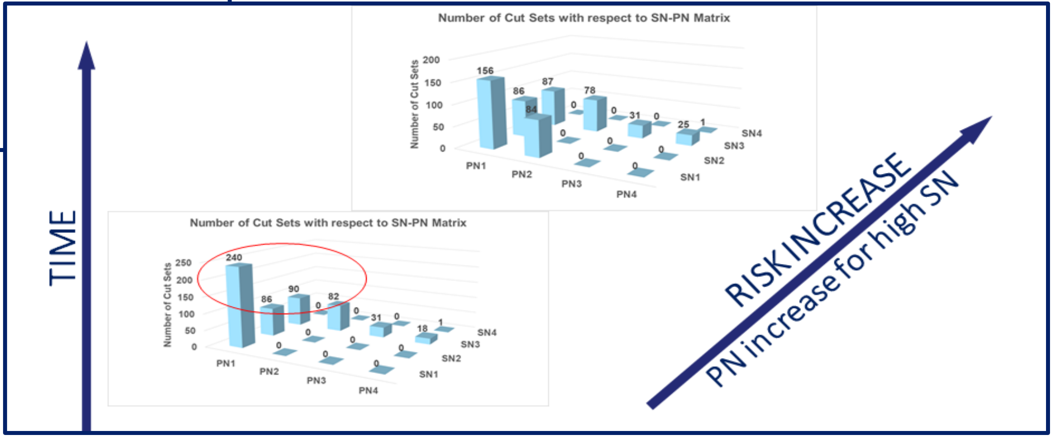




Number	CutSet ID	CutSet Description	Cut set probability	Order	SN	PN	RI
243	LF_FILTER_FAL	LF Filter Failure	5,18E-06	1	4	4	16

Risk assessment to date

Risk evolution in time



TN4
§4.3.2

Risk assessment estimates

Enhanced Risk Assessment

- Example

Risk assessment criteria check-list

No.	Risk acceptance criteria	Sat A	Sat B	Sat C	Sat D
1	At any point in time of the (extended) mission, the satellite probability of successful disposal, reassessed considering the status of the spacecraft and the future trends, is at least TBD.	✓	✓	✓	✓
2	At any point in time of the (extended) mission, the satellite probability of performing successful disposal using a “degraded strategy” is lower than TBD% of the overall probability of successful disposal.	✓	✓	✗	✓
3	At any point in time of the (extended) mission, the increase of failure combinations with “High Risk” is lower than TBD% wrt the baseline satellite configuration as per design (**).	✓	✓	✓	✗
4	……..				

Conclusions and perspectives

- Several approaches have been proposed, validated and integrated at satellite level in order to **more accurately assess the EoL probability**
- A generic reliability model has been developed in Excel to ‘easily’ apply these approaches
- The role and contribution of RAMS analyses has been demonstrated via practical applications on MSG and S1
- These quantitative and qualitative approaches can lead to **a better risk-awareness decision process** on satellite life extension, safe disposal and other applications as well.
- Reliability and Risk awareness estimates presented are all very relevant and are even most efficient when used in synergy, that is to say that **the most promising techniques are the ones that benefit of all these approaches** which together give the best possible knowledge on the spacecraft status at any point in time during its mission life. For this purpose, the data, methods, tools, processes and stakeholders required to apply operationally these quantitative/qualitative approaches have been described in detail.
- The RAMS analyses and proposed criteria will be even more important for future missions:
  - to comply to updated ISO24113 standard requirements
  - for mega-constellations, whose PMD success has been shown to be the major contributor to the future evolution of space objects in LEO
  - the propellant mass criterion could become less adequate or at least useful with future on-orbit refueling and servicing missions.

Conclusions and perspectives

- In addition to the classical risk analyses that are already or that could be performed in the EoL decision process (e.g. critical SPF list, list of Operation Life limited Items or those experiencing wear out, FEA, PRA, etc.) other risk analyses have been proposed and promoted by the study team to support decision-making process for extending in-orbit mission: a **Double failure matrix** (in §4.3.1) and an **Enhanced risk assessment** (in §4.3.2).
- They analyze combinations of faults that could lead to the loss of disposal capability, **assessing the related risk and identifying potential corrective/compensatory means**, already since the early phases of the satellite development process. They can be then reassessed **at any point in time of the satellite life** in case of faults/anomalies that change the satellite configuration, expected life or operation. They are therefore **particularly useful for satellites with enhanced lifetime that are in non-specified conditions**, and are prone to multiple failures due to "aging".
- They can be applied to **any type of spacecraft** (e.g. from a single satellite to a constellation) following a specific **set-up phase**, after which they can be used several times in a recurrent way.
- In addition, some **decision criteria have been suggested** (e.g. Risk Index, probability of disposal via nominal or degraded strategies) and implemented in the proof-of-concept of tool supporting these approaches.
- A very recent and preliminary application of the multi-disciplinary Enhanced Risk Assessment Technique on a real satellite has demonstrated its feasibility and interest for a **better risk-awareness decision on EoL. Future operational applications of this methodology are thus recommended**.

Conclusions and perspectives

- Way forward
  - To finalize the selection of the criteria, including their validation on previous / on-going missions
  - To apply operationally the recommended RAMS analyses and decision criteria
  - To further address the identified gaps:
    - Availability, accuracy and exploitation of TMs, both from ground tests and in orbit
    - Links with operational tools to extract, formatting and exploiting TMs
    - Radiation monitoring and estimation of lifetime limit linked to total dose
    - Evaluation and integration of MMOD probability
    - Approaches for 'New Space' missions and of low cost – low 'reliability' constellations
    - Contribution of OOS missions to the PMD success and evaluation of the overall system reliability
    - SDM requirements evolutions, in particular on RAMS topic
    - ….

THANK YOU FOR YOUR ATTENTION !

Task 1 analyses and results

Satellite unit degradation models

Satellite unit	Involved function	Degradation phenomena	Main causes / factor	Degradation timeframe	Observables	Recovery / corrective actions	Impact on the satellite life extension / EoL disposal	Comments including differences/similarities
SADM	Electrical power transmission Rotation of solar arrays	-bearings degradation :wear -motor degradation : isolation, open or short circuit	Mainly lubricant wear out Thermomechanical cycling onto components Contamination or isolation failures (low probability) MMOD (low probability)	Slow and continuous for the bearings. Unpredictable generally if contamination is concerned Random for motor failure	Motor currents, potentiometers position, temperatures	Lubrication homogenization via complete arrays rotations. Mostly no recoverable actions for lost functions. Ultimately, additional power provided by the battery if one wing power not sufficient (not applicable for S/C with only 1 SADM)	Medium/High since the loss of SADM rotation function is directly a diminution of the available power (up to half, or even the whole). Potential addition 'indirect' impact also on the AOCS control and thus on the propellant consumption.	The risk is mostly dependent to thermal conditions, in particular for LEO. The current within SADM also plays a role in the temperature. The rotation conditions and mechanical charging worst in LEO compared to other orbits. High risk for those satellites equipped with only one SADM (only one SA)
Other Propulsion units : valves	Monitoring, management and regulation of propellant flux and pressure	Seat mechanical wear motor degradation isolation, open or short circuit contamination ageing and radiation effects for SAPT	Cycling exceeded, material flaw in seat Environment temperature exceeded Particles trapped TID for electronics	slow and continuous but sharp increase of damage at a triggering level	State of valve, Pressures Temperatures, Motor current	Redundancy (if applicable). Design margins and qualification Fluidic branch isolation (if applicable) Book keeping and/or thermal gauging instead of PVT method with the SAPT	Medium since these units are necessary for the propulsion subsystem however no major degradation effects are expected, or classically observed in orbit	The risk is not changing vs. the altitude, but the risk is stronger for high cycles units. Hence a domain of cycles admissible that cannot be extended
Magneto torques bar	Attitude control and/or reaction wheels desaturation	No major degradation known / expected	ageing effects of thermal cycling	If any, very slow and unknown process	comparison of commanded and measured current	MTB are internally redundant. To use another AOCS actuator	Low since it is not usually used as nominal AOCS actuator. In addition no major degradation are expected	
Magneto meter	To provide an output used to estimate the Earth magnetic field direction and intensity	No major degradation except the ageing and radiation effects on the electronics	Mainly radiation effects as per a classical electronic units	Slow, continuous process	comparison of measured and expected Earth magnetic field direction/intensity	Usually a redundant Magnetometer is available, or other AOCS sensors may be used. To use a Earth magnetic field model for the purpose of MTB commanding	Low since it is not usually used as nominal AOCS sensor for the extension of the lifetime or for the de-orbit of the satellite	
Star Tracker	To provide attitude measurements or the precise attitude determination purpose	Lower accuracy of STR data. Impact on the attitude determination of AOCS Nominal mode	Radiation, Thermal cycles, Contamination due to external environment, Ageing	Slow, continuous process	Internal unit health check (quality index). Number of stars used in the field of view. Voltage&/Current. Operating temperature of CCD and equipment.	Usually a redundant STR is available. To adapt manoeuver strategies and/or to use other AOCS sensors (if available) even if they are less accurate	Medium / High since the STRs are indispensable to perform the EoL manouvers and lower performance and/or failures may lead to a degraded or emergency disposal	R&D studies have evaluated the feasibility of a Reduced de-orbiting mode using other AOCS sensors

Task 1 analyses and results

Satellite unit degradation models

Satellite unit	Involved function	Degradation phenomena	Main causes / factor	Degradation timeframe	Observables	Recovery / corrective actions	Impact on the satellite life extension / EoL disposal	Comments including differences/similarities
Gyroscope	the gyro measurement feeds the on board attitude estimation filter	Depending on the technology Drift and lower accuracy of the satellite angular rates estimation	Depending on the technology Radiation, Aging	Rapid and unknown degradation	Health monitoring by comparing measured angular rates with the ones derived from other AOCS sensors (STR). Technology specific gyro TMs.	Usually a redundant GYRO is available. Furthermore, the STRs are an alternative in terms of angular rates estimation (gyro-less mode)	Medium since GYROs are not completely indispensable for the attitude control. Other AOCS sensors are usually used	Maintenance operation (calibration) is performed to correct/reduce gyro bias. Some gyros have a limited lifetime compared to the satellite mission duration therefore they are not always ON. Other technologies are less impacted by degradation
GNSS	to compute accurate position, velocity and reference time using GPS / GAL signals	Degradation of orbit determination accuracy (position/velocity). Drift of the receiver clock	Radiation, Aging, thermal stress.	Slow, continuous process	Several TMs available: NOF_SV, GDOP, Time Quality Index Clock Frequency.	Usually a redundant GNSS is available. Furthermore, orbit restitution can be given by ground	Low since wear out known and taken into account in the AOCS control loop. Anyway other means for orbit determination can be used, and accepted, or the EoL disposal	No significant degradation phenomena expected for the RF section of GNSS. GNSS are generally integrated in LEO & MEO satellites only. More recently they are employed also in GEO satellites, mainly or the purpose of autonomous Electrical Orbit Raising
Earth sensor	to determine the roll and pitch angle of the satellite	Depending on the technology : 'telescope' degradation similar to STR and/or electronic units wear out	Depending on the technology : Radiation, Thermal cycles, Contamination, Ageing	Slow, continuous process	Depending on the technology	Depending on the technology and on the mission needs (e.g. nominal or back-up sensor)	Low since reliable unit and wear out having a minor impact on the attitude accuracy. In addition other AOCS units may be used	this sensor has been used mainly in the past, two main technologies exist. More recent missions no longer use this kind of sensor (STR usually preferred because of higher accuracy)
Rotary actuators mechanism	Rotation of elements like thrusters antennas, etc…	bearings degradation :wear motor degradation : isolation, open or short circuit	Cycling exceeded Environment estimation weak MMOD	Slow and continuous for the bearings. Random for motor failure or MM0D	Motor currents, potentiometers position, temperatures	Design, including safety margins, and qualification tests. redundancy for electrical motor parts lubrication homogenization : full range cycling for the mechanisms	From low to High depending on the RA case : RA for thrusters have high impact, RA for antennas have no life extension / EOL impact	The risk is higher for thruster arms exposed to highly changing thermal environment, so in fact both MMOD and thermal control are relying onto shielding thermal passive structure.
Other electronic units	Data Handling, Power conditioning, Telemetry and Telecommand	No major degradation except the ageing and radiation effects on the electronics (TID, TNID)	Mainly radiation effects and component ageing	Slow, continuous process	Many observables depending on the unit. Usually temperature, voltage, current, etc.	Usually a redundant avionic equipment is available Radiation Design Margin (of at least 1.2 wrt the expected radiation dose) taken into account in the design (radiation analyses and WCA)	Medium since even if the avionic equipment are indispensable for the mission, including the EoL maneuvers,. degradation of electronic units as usually a low/negligible impact on the unit if correctly designed	Radiation environment significantly varies from one orbital regime to another.

Task 1 analyses and results

Satellite unit degradation models

Satellite unit	Involved function	Degradation phenomena	Main causes / factor	Degradation timeframe	Observables	Recovery / corrective actions	Impact on the satellite life extension / EoL disposal	Comments including differences/similarities
Battery	electrical power storage and supply during eclipse	- Calendar aging which results in energy and power loss due to the storage - Fading : mainly the positive electrode is concerned, resulting in a capacity loss and internal resistance increase	- Storage conditions, mainly temperature and State Of Charge (SOC) - It is influenced by the battery operating conditions : temperature, Depth of Discharge, charge rate, etc.	Slow, continuous and 'well' known process which has already been modeled	Battery voltage, current and power are directly available from TM. Battery capacity decrease and internal resistance increase can be derived from these TMs.	Degradation taken into account in the design. Redundant cells usually available. If not sufficient, satellite power consumption, HW matrix or modes to be adapted.	Low/Medium since wear out known, monitored and mastered. In addition, power margins at satellite level (especially for the disposal since payload usually OFF) because EPS sized on worst case scenarios. No or few failures observed in orbit (at least on recent Lithium-Ion)	The risk may be higher for those satellites equipped with an electrical propulsion system which will require a given amount of power in order to supply the thrusters needed for the disposal. Different operating conditions (e.g. DoD, cycles) depending on the orbit (e.g. LEO v.s. GEO) thus different degradation impact/timeframe
Solar array	to generate electrical power from the incoming solar energy	Damage by radiation is the principal cumulative effect that degrades solar cells output. MMOD Failure of components (diodes)	Radiations : non-ionizing (atomic displacement) effects, while ionization has a minor effect. Power loss is also linked to solar flares and impact with micro-meteoroids High cycling temperatures or simply high temperatures	Slow, continuous and 'well' known process which has already been studied and modeled. Much higher and unpredictable degradation in case of solar flares and impact with micro-meteoroids	short circuit current (Isc), open circuit voltage (Voc) and maximum power (Pmax). Generated power. Thermal sensors on solar array can also contribute to aging characterization ,when implemented forth and backward on the panels	Degradation taken into account in the design, the margin of power is generally covering a certain loss of strings. Other recoveries If not sufficient : satellite power consumption reduction or modes adapted. Ultimately, additional power provided by battery	Low/Medium since wear out known, monitored and mastered. In addition, power margins at satellite level (especially for the disposal since payload usually OFF) because EPS sized on worst case scenarios.	The risk may be higher for those satellites equipped with an electrical propulsion system which will require a given amount of power in order to supply the thrusters needed for the disposal. The risk will be much higher in case of completely loss of one solar array (e.g. because of a failure of the Solar Array Drive Mechanism). The risk is higher for satellites having low power margins, typically small satellites on constellations
Chemical propulsion : THR	Attitude and/or orbit control	- Degradation of catalyst granules leading to lower thruster force and Isp - Thermal shock that destroys catalyst granules when rapidly heated - Thermal choke : propellant vaporization in the capillarity feed tube leading to a reduced (or no) propellant flow	- Trend strongly depends on the firing mode (pulse on time and pulse cycle period) and on the catalyst bed temperature and thermal cycles. - Linked to cold starts - Linked to THR design and low pressure and high temperature conditions	Slow and predictable evolution with the number of thruster activation	Thruster temperature profile during the burn. Thruster force and Isp evolution over time, derived by the realized ΔV w.r.t. the required one and/or by evaluating the duty cycles and the number of THR actuations	Thruster qualified with (expected) real operating conditions and with a multiplication factor on the lifetime. Usually redundant thrusters are available. If not sufficient, to adapt the EoL disposal manoeuvers strategy.	Medium / High since the THR are indispensable to perform the EoL maneuvers and lower performance and/or failures may lead to a degraded or emergency disposal	Degradation phenomenon applicable only to mono-propellant THRs and not to bi-propellant ones (no major degradation phenomena for this solution). The risk may be higher in case of a THR used at operating conditions different from the tested ones or beyond its qualified lifetime.

Task 1 analyses and results

Satellite unit degradation models

Satellite unit	Involved function	Degradation phenomena	Main causes / factor	Degradation timeframe	Observables	Recovery / corrective actions	Impact on the satellite life extension / EoL disposal	Comments including differences/similarities
Electrical propulsion : HET	Attitude and/or orbit control of electric satellites (sometimes including also RW desaturation)	Erosion of the ceramic walls of the anode chamber leading to the end of the life of the HET when the magnetic circuit is eroded and the magnetic field interrupted. Oxidation of the emitting elements of the cathode.	Erosion caused by the ion sputtering when the thruster is used. Contamination of the propellant	Slow, continuous and 'well' known process which has already been studied and modeled	The reference potential of the cathode (CRP), the discharge current, the current oscillation as well as the force and Isp of the thruster.	Thruster qualified with (expected) real operating conditions and with a multiplication factor on the lifetime. Usually redundant thrusters are available. If not sufficient, to adapt the EoL disposal manoeuvers strategy.	Medium / High since the HET are indispensable to perform orbit maneuvers (station keeping and/or disposal) in all electric satellites Lower performance and/or failures may lead to additional Xenon consumption and/or contingency manoeuvers. In addition, manoeuver duration will be even longer	The risk will be higher for those satellites (usually small and 'low cost') equipped with only one HET
Reaction wheels	Attitude control : providing kinetic momentum	Degradation of the ball bearings linked to the deterioration of lubrication over time and leading to an increased friction torque (dry and viscous frictions) Motor degradation : isolation, open of short circuit Electronics wear out	Insufficient or unstable film thickness leading to metal-on-metal contact between bearing balls and races. lubrication deterioration and zero-speed crossings can damage the wheel and limit its lifetime : speed of the wheel, number of remaining active wheels Radiation effects	Assumed to be linear with the time but also cases of rapid and premature degradations have been observed in orbit.	Higher friction torque, equivalent to higher torque (higher power demand) and higher temperature for the same commanded torque. Torque and friction are derived from motor current and speed measured values	Usually a redundant RW is available. If not sufficient, to adapt the attitude control and manoeuvers strategy (e.g. to use less RWs or alternative AOCS actuators)	Medium since RWs are the baseline actuators for the attitude control but AOCS law and EoL disposal strategies may be adapted in order to use less RWs or alternative AOCS actuators.	Valid only for RW equipped with a ball bearing system since those using a magnetic bearing system do not experience wear out effects. R&D studies have evaluated the feasibility of a Reduced de-orbiting mode using other AOCS sensors
Sun acquisition sensor	To provide an output used to estimate the Sun direction and therefore the satellite attitude	Change of the performance and response of the photovoltaic cell of the sensor	Aging phenomena due to the radiation environment	Slow, continuous and known process	Current output for a given and known Sun position which decreases over time	the parameters used by the AOCS to derive the position of the Sun are adjusted in order to compensate this wear out and to have consistent attitude information	Low since reliable unit and wear out known and taken into account in the AOCS control loop. In addition, other AOCS sensors are usually used instead or in addition of the Sun sensor	

Task 1 analyses and results

Reliability approaches for satellite units

After having presented in detail how the reliability approaches could be used on the different satellite units, some recommendations have been provided on the most promising solutions.

Satellite unit	Approach 2 : Health monitoring	Approach 2 : Rex and Bayesian techniques	Approach 3a : Prognostic based on stochastic models	Approach 3b : Model based prognostic	Approach 3c : Prognostic based on data trends	Conclusions and recommendations (per orbit or type of mission, if applicable)
SADM	Currently this is the approach that is more often used during operations However it might be not applicable if TM sampling is not adapted and/or if interesting TMs are not available (which is actually the case for several missions).	Evaluated and useful only for the same design on the same orbit. Hence very good for constellation at some point, but not good at all for single missions.	Approach leading to more accurate reliability figures but limited applicability because of the complexity and amount of data needed to apply this method	Physics of failure is good for new applications but must be focused on dominant failure modes in order to limit the complexity. It might be difficult to validate the model because of the lack of data	Not evaluated in the frame of this study but few data are usually available for this unit. Therefore it might be not really feasible	Currently Approach 2 (Health monitoring) is the approach that is more often used during operations Generally there is a need of disposing of more data and/or more accurate ones to apply the approaches identified here. Additional monitoring will be probably needed in some cases
Other propulsion units	Currently this is the approach that is more often used during operations However it might be not applicable if TM sampling is not adapted and/or if interesting TMs are not available (which is actually the case for several missions).	As a large fleet of units exist, a manufacturer Rex might be useful to better evaluate the reliability and lifetime of these units. The limitation is of course to have to keep a coherent design	Approach leading to more accurate reliability figures but limited applicability because of the complexity and amount of data needed to apply this method	Physics of failure for space application might not be preponderant then this is not among the preferred approaches	Not evaluated in the frame of this study but few data are usually available for this unit. Therefore it might be not really feasible	Currently Approach 2 (Health monitoring) is that more often used during operations. Approach 2 (REX) is recommended for heritage technologies. Generally there is a need of disposing of more data and/or more accurate ones to apply the approaches identified here. Additional monitoring will be probably needed in some cases
Magneto torques bar	Currently this is the approach that is more often used during operations Useful to check the correct behavior and performance of the Magneto torques bar	Not really needed because of the already low failure rate of this unit. Thus a huge amount of samples will be needed to derive a failure rate lower than the basic one	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Currently Approach 2 (Health monitoring) is that more often used during operations. No major improvements are needed for this unit for the decision-making process for the life extension or disposal
Magnetometer	Currently this is the approach that is more often used during operations Useful to check the correct behavior and performance of the Magnetometer	Not really needed because of the already low failure rate of this unit. Thus a huge amount of samples will be needed to derive a failure rate lower than the basic one	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Currently Approach 2 (Health monitoring) is that more often used during operations. No major improvements are needed for this unit for the decision-making process for the life extension or disposal

Task 1 analyses and results

Reliability approaches for satellite units

Satellite unit	Approach 2 : Health monitoring	Approach 2 : Rex and Bayesian techniques	Approach 3a : Prognostic based on stochastic models	Approach 3b : Model based prognostic	Approach 3c : Prognostic based on data trends	Conclusions and recommendations (per orbit or type of mission, if applicable)
Strar Tracker	Currently this is the approach that is more often used during operations Useful to check the correct behavior and performance of the STR and to improve the accuracy of the reliability models with real operating temperatures and not the ones computed at CDR	Useful to derive less pessimistic failure rate and therefore to choose/optimize the architecture but not useful for the decision on the life extension or EoL disposal	Lower benefits are expected compared to other approaches, especially because of the complexity and amount of data needed to apply this method. In addition, wear out phenomena are not so evident, or at least severe	Unit supplier develops mathematical model to simulate/evaluate the performance of unit. This approach could be useful to predict the performance. Not a clear/complete view on the accuracy and validity of these models	For sure it could improve the health monitoring and the investigation of anomalies. Currently few/no practical use mainly because of the amount of data needed.	Currently Approach 2 (Health monitoring) is that more often used during operations. It is recommended as well as the Approach 3c that is seen as a very promising solution to further improve the health monitoring and the decision process. Approach 3b needs maybe to be further evaluated with the involvement of the supplier
Gyroscopes	Currently this is the approach that is more often used during operations Useful to check the correct behavior and performance of the GYRO and to improve the accuracy of the reliability models with real operating temperatures and not the ones computed at CDR	Useful to derive less pessimistic failure rate and therefore to choose/optimize the architecture but not useful for the decision on the life extension or EoL disposal	Lower benefits are expected compared to other approaches, especially because of the complexity and amount of data needed to apply this method. In addition, wear out phenomena are not so evident, or at least severe	Not evaluated in the frame of this study since no valid model describing the degradation phenomenon has been found	For sure it could improve the health monitoring and the investigation of anomalies. Currently few/no practical use mainly because of the amount of data needed.	Currently Approach 2 (Health monitoring) is that more often used during operations. It is recommended as well as the Approach 3c that is seen as a very promising solution to further improve the health monitoring and the decision process.
GNSS	Currently this is the approach that is more often used during operations Useful to check the correct behavior and performance of the GNSS and to improve the accuracy of the reliability models with real operating temperatures and not the ones computed at CDR	Useful to derive less pessimistic failure rate and therefore to choose/optimize the architecture but not useful for the decision on the life extension or EoL disposal.	Lower benefits are expected compared to other approaches, especially because wear out phenomena are not so evident, or at least severe, for this unit	Lower benefits are expected compared to other approaches, especially because wear out phenomena are not so evident, or at least severe, for this unit	For sure it could improve the health monitoring and the investigation of anomalies. Currently few/no practical use mainly because of the amount of data needed.	Currently Approach 2 (Health monitoring) is that more often used during operations. It is recommended as well as the Approach 3c that is seen as a very promising solution to further improve the health monitoring and the decision process.
Earth sensor	Currently this is the approach that is more often used during operations Useful to check the correct behavior and performance of the Sensor	Not really needed because of the already low failure rate of this unit. Thus a huge amount of samples will be needed to derive a failure rate lower than the basic one	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Currently Approach 2 (Health monitoring) is that more often used during operations. No major improvements are needed for this unit for the decision-making process for the life extension or disposal

Task 1 analyses and results

Reliability approaches for satellite units

Satellite unit	Approach 2 : Health monitoring	Approach 2 : Rex and Bayesian techniques	Approach 3a : Prognostic based on stochastic models	Approach 3b : Model based prognostic	Approach 3c : Prognostic based on data trends	Conclusions and recommendations (per orbit or type of mission, if applicable)
Rotary actuators mechanisms	Currently this is the approach that is more often used during operations However it might be not applicable if TM sampling is not adapted and/or if interesting TMs are not available (which is actually the case for several missions).	Evaluated and useful only for the same design on the same orbit. Hence very good for constellation at some point, but not good at all for single missions.	Approach leading to more accurate reliability figures but limited applicability because of the complexity and amount of data needed to apply this method	Physics of failure is good for new applications but must be focused on dominant failure modes in order to limit the complexity. It might be difficult to validate the model because of the lack of data	Not evaluated in the frame of this study but few data are usually available for this unit. Therefore it might be not really feasible	Currently Approach 2 (Health monitoring) is the approach that is more often used during operations A combined approach is recommended for best decision. The approach is new but promising since incorporating the benefits of model prognosis, random failures on design and MMOD, and the possibility to have bayesian updating.. Generally there is a need of disposing of more data and/or more accurate ones to apply the approaches identified here. Additional monitoring will be probably needed in some cases
Other electronics units	Currently this is the approach that is more often used during operations Useful to check the correct behavior and performance of the Avionic units. Specific actions may be defined in case of anomalies	Useful to derive less pessimistic FIT for the Avionic units but not useful for the decision on the life extension or EoL disposal	Lower benefits are expected compared to other approaches, especially because wear out phenomena are not so evident, or at least severe, for this unit	Approach : Prognostic based on radiation drifts. Promising approach but to be validated with real WCA in order to conclude on its validity / interest	For sure it could improve the health monitoring and the investigation of anomalies. Currently few/no practical use mainly because of the amount of data needed.	Currently Approach 2 (Health monitoring) is that more often used during operations. It is recommended as well as the Approach 3c that is seen as a very promising solution to further improve the health monitoring and the decision process. In addition, the evaluation of the lifetime of electronics units because of radiation effects (TID) is seen as an interesting approach to be further evaluated on real cases.

Task 1 analyses and results

Reliability approaches for satellite units

Satellite unit	Approach 2 : Health monitoring	Approach 2 : Rex and Bayesian techniques	Approach 3a : Prognostic based on stochastic models	Approach 3b : Model based prognostic	Approach 3c : Prognostic based on data trends	Conclusions and recommendations (per orbit or type of mission, if applicable)
Battery	Useful to check the correct behavior and performance of the batteries but estimation not always possible or accurate.	Useful to derive less pessimistic FIT but extended amount of cumulated hours is needed. Not necessarily or directly reusable for different/new technologies or mission with different operating conditions	Interesting approach but requiring a huge amount of data to be followed and especially to provide accurate results. Today examples in literature mainly based on engineering judgment therefore representativeness may be questionable.	Very useful approach to predict the future performance and the remaining useful lifetime of the batteries. Currently this is the approach that is more often used.	For sure it could improve the health monitoring and the investigation of anomalies. Currently few/no practical use mainly because of the amount of data needed.	Approach 3b together with Approach 2 (health monitoring) are the ones currently used operationally. They are recommended as well as the Approach 3c that is seen as a very promising solution to further improve the health monitoring and the decision process
Solar array	Useful to check the correct behavior and performance of the solar arrays. Specific actions may be defined in case of low/negative power margins. Currently this is the approach that is more often used during operations	Failure rate of cell usually already derived with a REX. Valid and useful only for the same design on the same orbit. Hence very good for constellation at some point, but not good at all for single missions.	Approach potentially leading to more accurate reliability figures since wear out effects are taken into account. However it can be used only on satellite having the same orbit/technology because of the amount of data needed to derive a correct model	Currently this is the approach that is used to predict the performance degradation and therefore to size the SA accordingly. But the major drawback from lacking the statistical data, and hence confidence interval.	Allowing to more easily detect any abnormal behavior and to anticipate some actions before the occurrence of more severe failures.	On a short term, risk assessment based on health status and simple model prognostic are complementary A combined approach is recommended for best decision. The approach is new but promising since incorporating the benefits of model prognosis, random failures on design and MMOD, and the possibility to have bayesian updating.
Chemical propulsion : THR	Useful to check the correct behavior and performance of the THR via direct or indirect TMS. Specific actions may be defined in case of anomalies or rapid THR degradations Currently this is the approach that is more often used during operations	Currently not applied since difficult to gather enough data on similar units. In addition, THR are usually not always ON, therefore it is difficult to achieve a number of cumulated hours leading to reasonable failure rates.	Lower benefits expected compared to other approaches, especially because of the complexity and amount of data needed to apply this method	Useful to predict the THR performance but accuracy and validity questionable in case of a THR used at operating conditions different from the tested ones or beyond its qualified lifetime	For sure it could improve the health monitoring and the investigation of anomalies. Currently few/no practical use mainly because of the amount of data needed.	Approach 2 (health monitoring) is the one currently used operationally. It is recommended as well as the Approach 3c that is seen as a very promising solution to further improve the health monitoring and the decision process
Electrical propulsion : HET	Useful to check the correct behavior and performance of the HET. Specific actions may be defined in case of anomalies or rapid HET degradations Currently this is the approach that is more often used during operations	Approach currently used by some suppliers since unit not really covered by reliability standards. Useful to derive less pessimistic FIT and therefore to choose/optimize the architecture but not useful for the decision on the life extension or EoL disposal.	Lower benefits are expected compared to other approaches, especially because of the complexity and amount of data needed to apply this method. In addition, operating principles are quite complex to be 'simply' modeled	Useful to predict the HET performance but accuracy and validity questionable in case of a THR used at operating conditions different from the tested ones or beyond its qualified lifetime	For sure it could improve the health monitoring and the investigation of anomalies. Currently few/no practical use mainly because of the amount of data needed.	Approach 2 (health monitoring) is the one currently used operationally. It is recommended as well as the Approach 3c that is seen as a very promising solution to further improve the health monitoring and the decision process

Task 1 analyses and results

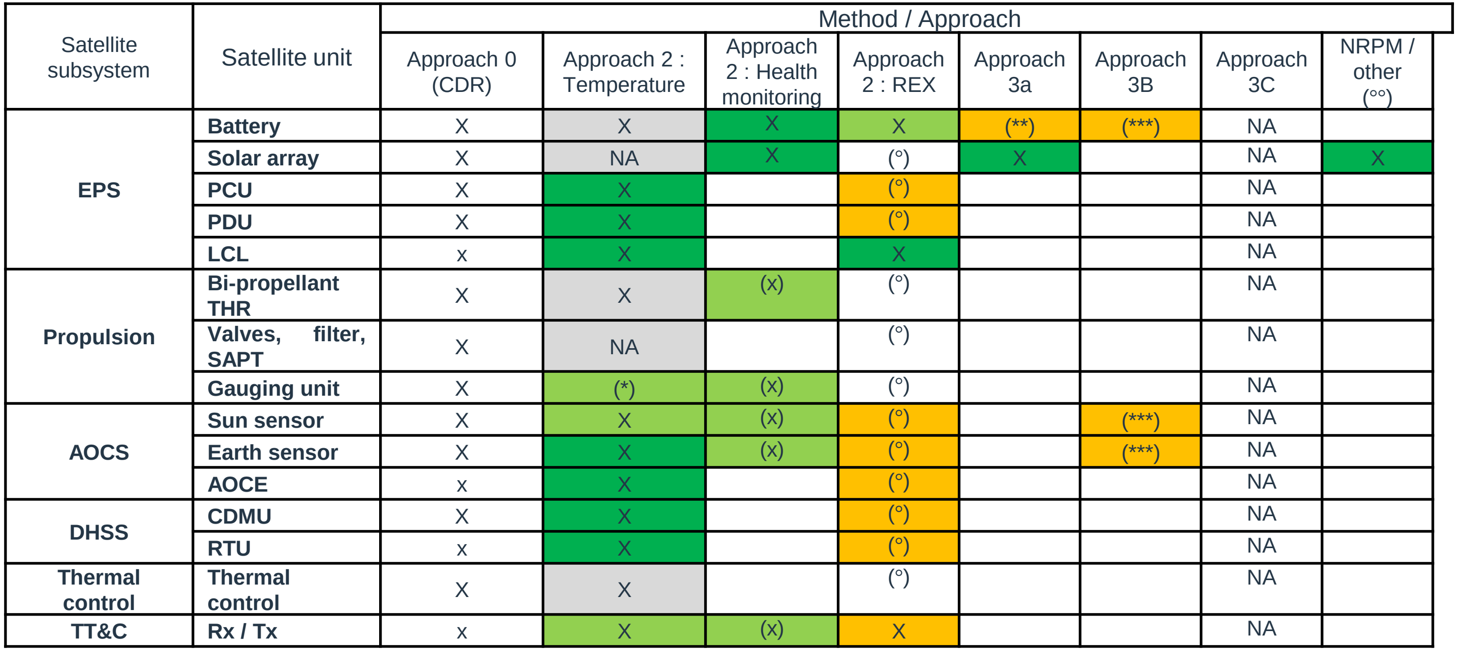
Reliability approaches for satellite units

Satellite unit	Approach 2 : Health monitoring	Approach 2 : Rex and Bayesian techniques	Approach 3a : Prognostic based on stochastic models	Approach 3b : Model based prognostic	Approach 3c : Prognostic based on data trends	Conclusions and recommendations (per orbit or type of mission, if applicable)
Reaction wheels	Currently this is the approach that is more often used during operations Useful to check the correct behavior and performance of the RWs. Specific actions may be defined in case of anomalies or rapid RW degradations	Useful to derive less pessimistic FIT and therefore to choose/optimize the architecture but not useful for the decision on the life extension or EoL disposal	Interesting approach but requiring a huge amount of data to be followed and especially to provide accurate results. Today examples in literature mainly based on engineering judgment therefore representativeness may be questionable.	Unit supplier develops mathematical model to simulate/evaluate the performance of unit. This approach could be useful to predict the RW performance. Not a clear/complete view on the accuracy and validity of these models	For sure it could improve the health monitoring and the investigation of anomalies. Currently few/no practical use mainly because of the amount of data needed.	Currently Approach 2 (Health monitoring) is that more often used during operations. It is recommended as well as the Approach 3c that is seen as a very promising solution to further improve the health monitoring and the decision process. Approach 3b needs maybe to be further evaluated with the involvement of the supplier
Sun sensor	Currently this is the approach that is more often used during operations Useful to check the correct behavior and performance of the Sun Sensor	Not really needed because of the already low failure rate of this unit. Thus a huge amount of samples will be needed to derive a failure rate lower than the basic one	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Similar to the one discussed for SA. Useful to predict the performance degradation of the Sun sensor but not needed to improve the decision-making process for the life extension or disposal	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Currently Approach 2 (Health monitoring) is that more often used during operations. No major improvements are needed for this unit for the decision-making process for the life extension or disposal
Thermal control	Currently this is the approach that is more often used during operations Useful to check the correct behavior and performance of the thermal control and to improve the accuracy of the reliability models with real operating temperatures and not the ones computed at CDR	Useful to derive less pessimistic FIT for the heaters but not useful for the decision on the life extension or EoL disposal. No need to reassess the failure rate of the heaters in the future since it is already very low	Not really needed and applicable to this unit since the degradation phenomenon is negligible, and the unit already high reliable	Mathematical models are built during the development process in order to define the design of the thermal control subsystem and to guarantee the correct temperature ranges even in worst case scenarios	For sure it could improve the health monitoring and the investigation of anomalies. Currently few/no practical use mainly because of the amount of data needed.	Currently Approach 2 (Health monitoring) is that more often used during operations. It is recommended as well as the Approach 3c that is seen as a very promising solution to further improve the health monitoring and the decision process. These approaches could be exploited also by thermal engineers to refine/update the parameters taken in their models

Task 2 analyses and results

Reliability approaches validated and recommended

MSG

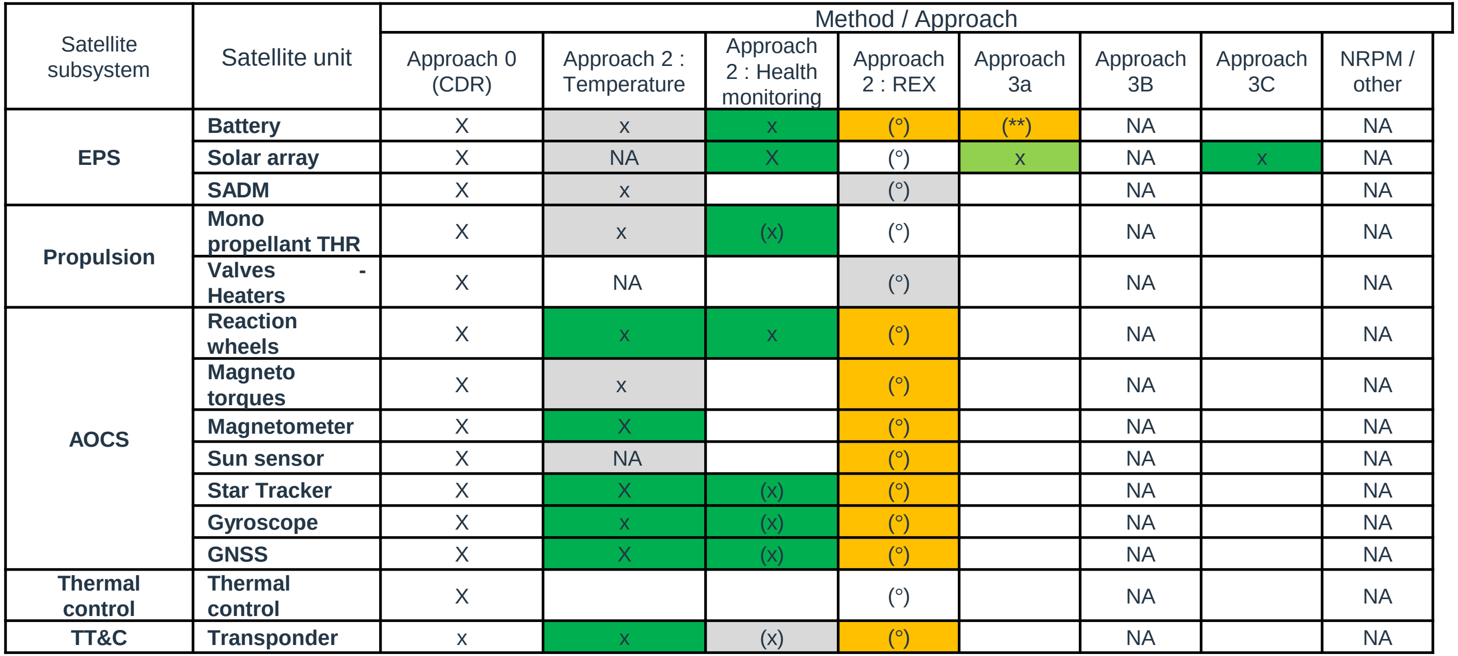


Satellite subsystem	Satellite unit	Method / Approach							
		Approach 0 (CDR)	Approach 2 : Temperature	Approach 2 : Health monitoring	Approach 2 : REX	Approach 3a	Approach 3B	Approach 3C	NRPM / other (°°)
EPS	**Battery**	X	X	X	X	(**)	(***)	NA	
	Solar array	X	NA	X	(°)	X		NA	X
	PCU	X	X		(°)			NA	
	PDU	X	X		(°)			NA	
	LCL	x	X		X			NA	
Propulsion	**Bi-propellant THR**	X	X	(x)	(°)			NA	
	Valves, filter, SAPT	X	NA		(°)			NA	
	Gauging unit	X	(*)	(x)	(°)			NA	
AOCS	**Sun sensor**	X	X	(x)	(°)		(***)	NA	
	Earth sensor	X	X	(x)	(°)		(***)	NA	
	AOCE	x	X		(°)			NA	
DHSS	**CDMU**	X	X		(°)			NA	
	RTU	x	X		(°)			NA	
Thermal control	**Thermal control**	X	X		(°)			NA	
TT&C	**Rx / Tx**	x	X	(x)	X			NA	

Task 2 analyses and results

Reliability approaches validated and recommended

Sentinel 1



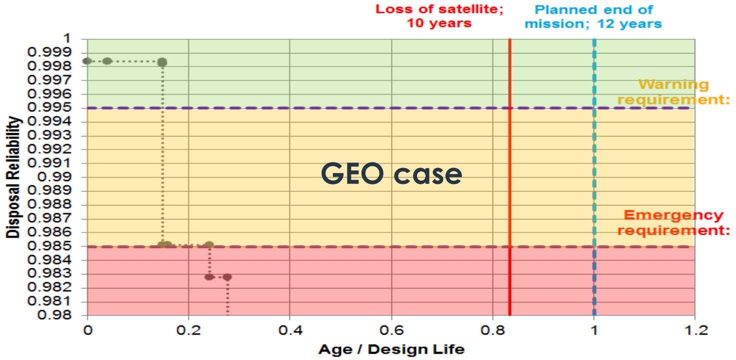
Satellite subsystem	Satellite unit	Method / Approach							
		Approach 0 (CDR)	Approach 2 : Temperature	Approach 2 : Health monitoring	Approach 2 : REX	Approach 3a	Approach 3B	Approach 3C	NRPM / other
EPS	**Battery**	X	x	x	(°)	(**)	NA		NA
	Solar array	X	NA	X	(°)	x	NA	x	NA
	SADM	X	x		(°)		NA		NA
Propulsion	**Mono propellant THR**	X	x	(x)	(°)		NA		NA
	Valves - Heaters	X	NA		(°)		NA		NA
AOCS	**Reaction wheels**	X	x	x	(°)		NA		NA
	Magneto torques	X	x		(°)		NA		NA
	Magnetometer	X	X		(°)		NA		NA
	Sun sensor	X	NA		(°)		NA		NA
	Star Tracker	X	X	(x)	(°)		NA		NA
	Gyroscope	X	x	(x)	(°)		NA		NA
	GNSS	X	X	(x)	(°)		NA		NA
Thermal control	**Thermal control**	X			(°)		NA		NA
TT&C	**Transponder**	x	x	(x)	(°)		NA		NA

Annex: short term criterion thresholds definition and validation

- How to select the thresholds so that the short term criterion could be useful for the EoL disposal without being, at the same time, too stringent ?
- If already applicable, would have this criterion helped in achieving a higher PMD success rate ?
- → Application of the short term reliability criterion on previous missions and evaluation of the recommendations
  - For those S/C with unsuccessful / insufficient EoL disposal

    Good criterion if Disposal warned --> potentially successful disposal
    Good criterion if Disposal recommended --> successful disposal
    Criterion not strict enough : S/C lost anyway even with the criterion
  - For those S/C having succeeded the EoL disposal

    Criterion too strict : too early or not needed recommendation
    Probably good : disposal recommended
    S/C disposed before criterion is even met
    Average mission duration loss



Preliminary results have shown that, if correctly defined, the short term reliability critetion could have avoided several satellites to loose / left in orbit several satellites, both in LEO and GEO !

However it can have an impact on the mission lifetime and cannot be always the magic solution to PMD !

In this sense, an optimization tool is envisaged in order to find a good compromise between impact on the mission and the sustainability of space environment