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The importance of the Lifetime analysis for Constellation Management

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Abstract

The Galileo System is a satellite-based navigation system that aims at providing a number of guaranteed services to users equipped with Galileo-compatible receivers. Since December 2016, when initial services were declared by the European Union, the number of users has been increasing every day. The Galileo Control Centre (GCC-D) in Oberpfaffenhofen is one of two control centres responsible of operating the Galileo constellation, managing a growing fleet of twenty-eight spacecrafts flying at MEO altitudes and consisting of two different satellite families: IOV and FOC.

The main goal of the Galileo Lifetime Analysis is to provide an estimation of the remaining lifetime for the IOV and FOC satellites. The outcome of the analysis can be used for the management of the constellation to target accordingly the orbital plan for the upcoming launches and plan, when needed, relocation manoeuvre.

The Lifetime Analysis not only focuses on the evolution of the consumables but also considers additional parameters reflecting the aging of the related equipment. By comparing the evolution of these parameters with the baseline, an indication of possible upcoming issue can be promptly detected and reported. This allows the adoption of mitigating measures to extend the life of the equipment and facilitates the planning of the acquisition of spare resources in due time.

Similarly, a positive trend might be identified, that allows operating an equipment beyond its nominal lifetime. By forecasting events which might impact the ability to perform disposal manoeuvres, it is possible to exploit each spacecraft until the very end of its lifetime. The update of the Galileo Constellation Lifetime Analysis is nominally performed on a yearly basis; however, there may be special events that could lead to ad-hoc assessment.

The objective of this paper it is to describe the process that has been defined to identify the relevant telemetries to be used to assess the remaining lifetime of the spacecraft and its capacity to provide service. In particular, it will describe how the different TMs is analysed and how the outcome is currently used for constellation management purposes.

Keywords: Lifetime analysis, Galileo, Constellation management

Acronyms/Abbreviations

AOCS, Attitude and Orbit Control Subsystem
CMCU, clock monitoring and control unit
CS, Commercial Service
EMU, Environmental Monitoring Unit
EPS, Electrical Power Subsystem
FDIR, Failure Detection Isolation Recovery
FGUU, Frequency generation and Up Conversion Unit
FMECA, Failure Mode, Effects, and Criticality Analysis
FOC, Full Operational Capability
GCC-D, Galileo Control Centre Deutschland
IOV, In Orbit Validatio
MEO, Medium Earth Orbit
MTTF, Mean Time to Failure
PCDU, Power Control Distribution Unit
PFSU, Platform Security Unit
PHM, Passive Hydrogen Maser
PRS, Public Regulated Service
RAFS, Rubidium Atomic Frequency Standard
RTU, remote terminal unit
RW, Reaction Wheel
SADM, Solar Array Drive Mechanism
SAR, Search and Rescue
SoL, Safety of Life
TCS, Thermal Control Subsystem
TM, telemetries
TTC, Telemetry, Tracking and Command

NSGU, Navigation Signal Generator Unit
OS, Open Service
TWT, Travelling Wave Tube

1. Introduction

The Galileo System is a satellite-based navigation system that aims at providing a number of guaranteed services to users equipped with Galileo-compatible receivers. Since December 2016, when initial services were declared by the European Union, the number of users has been increasing every day. The Galileo Control Centre (GCC-D) in Oberpfaffenhofen is one of two control centres responsible of operating the Galileo constellation, managing a growing fleet of twenty-eight spacecrafts flying at Medium Earth Orbit (MEO) altitudes and consisting of two different satellite families: IOV and FOC.

2. Galileo Constellation

The final configuration of the Galileo constellation foreseen 30 satellite of which 6 are spares in a so-called Walker 24/3/1 constellation. Each satellite will broadcast precise time signals, ephemeris and other data.

The Galileo satellite constellation has been optimized to the following nominal constellation specifications: [1]

- circular orbits (satellite altitude of 23 222 km)
- orbital inclination of 56 degree
- three equally spaced orbital planes uniformly distributed round the equator at interval of 120 degree
- eight operational satellites, equally spaced in each plane
- two spare satellite (also transmitting) in each plane

The altitude of the satellites has been chosen to avoid gravitational resonances so that, after initial orbit optimisation, only one station-keeping manoeuvres will be needed during the lifetime of a satellite. The altitude chosen also ensures a high visibility of the satellites.

The position constraints for individual satellites are set by the need to maintain a uniform constellation, for which it is specified that each satellite should be within +/- 2° of its nominal position relative to the adjacent satellites in the same orbit plane. The in-plane accuracy is equivalent to a relative tolerance of over 1000 km but requires very careful adjustment of the satellite velocity to ensure that the orbit period of all the satellites is kept precisely the same.

The spare satellite in each orbit plane ensures that in case of failure the constellation can be repaired quickly by moving the spare to replace the failed satellite. This could be done in a matter of days, rather than waiting for a new launch to be arranged which could take many months. [2]

At the end of life (be it after a nominal mission or through a failure), the satellite shall be transferred to a graveyard orbit with a semi-major axis at least 300 km greater than the nominal orbit

Each Galileo satellite will broadcast 10 different navigation signals making it possible for Galileo to offer the open (OS), safety-of-life (SOL), commercial (CS) and public regulated services (PRS). The frequencies used by the satellites are within the 1.1 to 1.6 GHz band (see fig.1): a range of frequencies particularly well suited for mobile navigation and communication services.

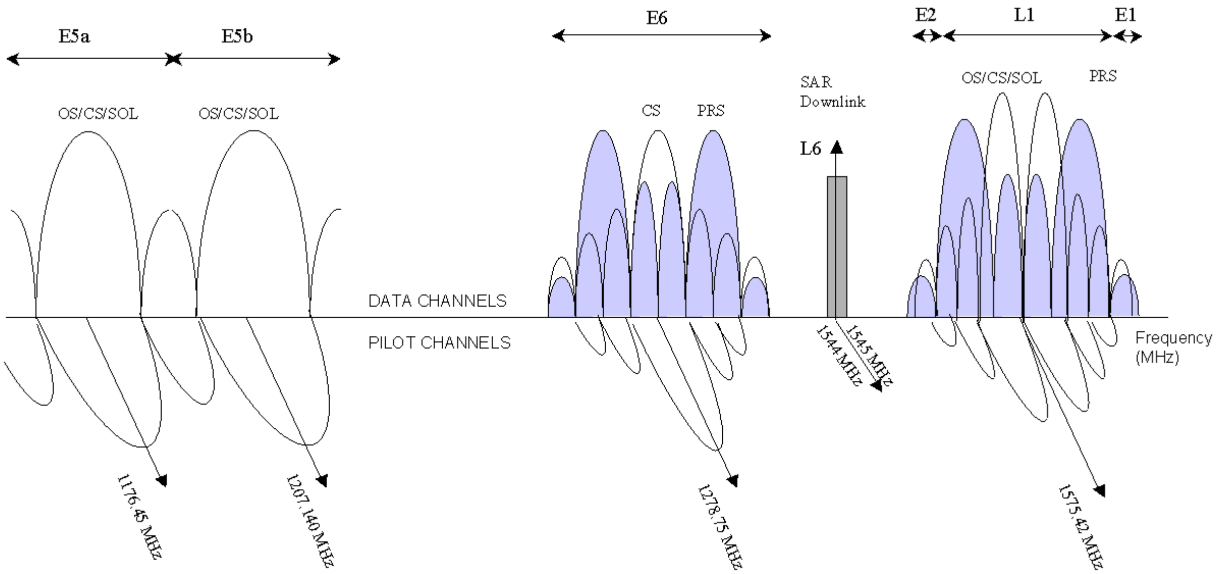


Fig. 1. Galileo Broadcasted Navigation frequency and services [3]

In particular [3]:

- The Open Service (OS) results from a combination of open signals, free of user charge, and provides position and timing performance competitive with other GNSS systems.
- The Safety-of-Life Service (SoL) improves the open service performance through the provision of timely warnings to the user when it fails to meet certain margins of accuracy (integrity). It is envisaged that a service guarantee will be provided for this service.
- The Commercial Service (CS) provides access to two additional signals, to allow for a higher data throughput rate and to enable users to improve accuracy. The signals are encrypted. It is envisaged that a service guarantee will be provided for this service.
- The Public Regulated Service (PRS) provides position and timing to specific users requiring a high continuity of service, with controlled access. Two PRS navigation signals with encrypted ranging codes and data will be available.
- The Galileo support to the Search And Rescue (SAR) service represents the contribution of Europe to the international COSPAS-SARSAT co-operative effort on humanitarian Search and Rescue activities. Galileo is to play an important part of the Medium Earth Orbit Search and Rescue system (MEOSAR). Galileo satellites will be able to pick up signals from emergency beacons carried on ships, planes or persons and ultimately send these back to national rescue centres. From this, a rescue centre can know the precise location of an accident. At least one Galileo satellite will be in view of any point on Earth so near real-time distress alert is possible. In some cases, feedback could be sent back to a beacon, something which is only made possible by Galileo.

2.1 Overview of Galileo Constellation

The Galileo satellite consists mainly in two elements, platform and payload subsystems.

The payload subsystem is the heart of the Galileo spacecraft and includes the navigation payload and the SAR payload. In particular, it consists of the following units [4]:

- Two Passive Hydrogen Maser (PHM) clocks expected to be used as master clock on board the spacecraft. They are atomic clocks which use the ultra-stable 1.4 GHz transition in a hydrogen atom to measure time to within 0.45 ns over 12 hours.

- Two Rubidium Atomic Frequency Standard (RAFS) clock to be used in case of maser clock failure. It is accurate to within 1.8 ns over 12 hours.

- The clock monitoring and control unit (CMCU) that provides the interface between the four clocks and the navigation signal generator unit (NSGU). It passes the signal from the active master clock to the NSGU and ensures that the frequencies produced by the master clock and the active spare are in phase, so that the spare can take over instantly should the master clock fails.

- The navigation signal generator unit, which includes internal cold redundancy, receives the up-linked navigation data and uses them to generate the navigation signals in the appropriate format, performs the PRN encoding and the modulation of the 3 navigation signals (E5a + E5b, E6 and L1) and passes them to the Frequency Generation and Up-conversion Unit (FGUU) which performs the up- conversion into L-band of the 3 signals.

- A L-band antenna transmits the navigation signals in the 1200-1600 MHz frequency range.

- A C-band antenna receives signals containing mission data from Galileo Uplink Stations. This includes data to synchronise the on-board clocks with a ground-based reference clock and integrity data which contains information about how well each satellite is functioning. The integrity information is incorporated into the navigation signal for transmission to users.

- A SAR (Search and Rescue) antenna that picks up distress signals from beacons on Earth and transmits them to a ground station for forwarding to local rescue services

- The remote terminal unit (RTU) is the interface between all the payload units and the on-board computer.

The platform units consist in all the different subsystems that are needed for the payload to work as expected. In particular, the main platform units are reported hereafter [4]:

- Command and data handling subsystems that includes the on-board-computer and the on-board software. It controls all aspects of spacecraft and payload functioning; it is responsible of the handling of the telecommands received by ground and of the generation and coding of the house-keeping telemetries from the different units.

- Telemetry, Tracking and Command (TTC) Subsystem with S-Band Transponder and two low-gain, omni-directional antennas. The S-band antennas transmit housekeeping data about the payload and spacecraft to ground control and, in turn, receive commands to control the spacecraft and operate the payload. The S-band antennas also receive, process and transmit ranging signals that measure the satellite's altitude to within a few metres.

- Electrical Power Subsystem (EPS) responsible of providing electrical power to all connected loads during the different mission phases. It consists of the following units:
  - Solar Arrays
  - Solar Array Drive Mechanisms (SADM) that it is the drive mechanism that connects the solar arrays to the spacecraft and rotates them slowly so that the surface of the arrays can always remain perpendicular to the Sun's rays.
  - Batteries that provide the necessary power during eclipses (e.g. when the Solar Array are not illuminated by the sun)

  - Power Conditioning and Distribution Unit (PCDU) that regulates and controls power from the solar arrays and batteries and distributes it to all the spacecraft's subsystems and payload.

- Thermal Control Subsystem (TCS) with thermistors, heaters, heat-pipes and space radiators. The space radiators are heat exchangers that radiate waste heat, produced by the units inside the spacecraft, to deep space and thus help to keep the units within their operational temperature range.

- Attitude and Orbit Control System (AOCS) Subsystems based on earth sensors, sun sensors, gyros, reaction wheels and magnetic torquers. In particular, the infrared Earth sensors and the Sun sensors both help to keep the spacecraft pointing at the Earth. The infrared Earth sensors do this by detecting the contrast between the cold of deep space and the heat of the Earth's atmosphere. The Sun sensors are visible light detectors which measure angles between their mounting base and incident sunlight. It is main functionality it is to keep the attitude of the spacecraft as required during the different mission phase and to keep the pointing of the solar array toward the sun. The primary pointing target during nominal mission is to have the NAVANT/SARANT boresight always pointing towards the Earth's centre.

- Propulsion Subsystem with a mono-propellant system with one tank and 8 thrusters divided in a nominal and redundant branch.

- Laser Retro-Reflectors that allows the measurement of the satellite's altitude to within a few centimetres by reflecting a laser beam transmitted by a ground station.

- Platform Security Unit (PFSU), environmental monitoring unit (EMU), structures and harness

3. Goals of Galileo the Lifetime analysis

The main goal of the Galileo Lifetime Analysis is to provide an estimation of the remaining lifetime for the IOV and FOC satellites. The outcome of the analysis can be used for the management of the constellation to target accordingly the orbital plane for the upcoming launches and plan, when needed, relocation manoeuvre.

The Lifetime analysis is meant to analyse the evolution and consumption trend of units with a defined lifetime. This lifetime of a specific unit is nominally larger or equal to the expected satellite lifetime, and the main objective is to analyze the trend of the key parameters of these units, to confirm (or not) that the aging and consumption trend is occurring as per predicted behavior and that the expected unit lifetime is predicted to be achieved. In fact, the lifetime analysis not only focuses on the evolution of the consumables, but it also considers additional parameters reflecting the aging of the related equipment. By comparing the evolution of these parameters with the baseline, an indication of possible upcoming issue can be promptly detected and reported.

This allows the adoption of mitigating measures to extend the life of the equipment and facilitates the planning of the acquisition of spares resources in due time. Similarly, a benign trend might be identified, that allows operating an equipment beyond its nominal lifetime. Additionally, detected out of family or out of specifications trends are assessed, together with their impact on unit performance and satellite functionality.

This type of analysis is satellite specific, meaning that the lifetime of each satellite can be independently calculated. Being Galileo a constellation of spacecraft, multi-satellite analysis allows a further step of data analysis and intra-satellite comparison, improving the results, in addition to the possibility to identify specific root causes for out of family behaviors (specific orbit, specific launch, production batch, etc…).

Another type of lifetime analysis that can be performed in parallel to the previous one is a statistical analysis of random failures. Analyzing the number and type of unit failures and comparing on-orbit data against expected failure rates from FMECA documents, it is possible to determine if the failure rate of the flying satellite constellation is within the expected values or not and to predict the likelihood and timing of future unit/satellite failures. This analysis is often called "Reliability Analysis".

This type of analysis can be either satellite specific or performed at constellation level. Since it is a statistical analysis, performing it at constellation level allows achieving more reliable and more meaningful results, determining the expected lifetime of the operational Galileo constellation.

Probability of sudden unit failures over time is generally modelled following Weibull distribution or exponential distribution. In general, the failure time, or the probability to incur in a failure during the lifetime, is function of on-orbit time, redundancy configuration and most importantly the parameter ʎ, the failure rate coefficient. Predicted values of this parameter for each satellite unit, or subsystem, or system, are determined during manufacturing and are usually available in the FMECA documentation. These values can be compared to and possibly adjusted for real life data, allowing determining the likelihood of failure and expected satellite/constellation lifetime. Anyway, a proper fine-tune of the probability of failure can be done only for a limited number of units.

By forecasting failures which may lead to the inability to perform disposal manoeuvres, it is possible to exploit each spacecraft until the very end of its lifetime. The update of the Galileo Constellation Lifetime Analysis is nominally performed on a yearly basis; however, there may be special events that could lead to ad-hoc assessment.

4. **Galileo Lifetime time analysis process description**

4.1 Units and subsystems analysed in the Lifetime analysis report

The Galileo Lifetime Analysis report contains the analysis of a set of data from different units and subsystems, e.g. the ones that present performance degradation or consumption with time and that can limit the operational lifetime of a satellite. All the parameters that are evaluated in the frame of the Lifetime Analysis have been chosen after a comprehensive screening of the on-board equipment and of all the available spacecraft telemetry. It is important to mention that the parameters that are not included in the Lifetime Analysis because not relevant for the scope (i.e., their value and evolution do not show any trend that can be used for lifetime estimation) are still being regularly monitored and reported in the daily, weekly, and yearly reports.

The selected unit for which the lifetime analysis is executed are the following one:

- Solar Array Degradation: the measured Solar Array decrease of generated power with time is compared against the expected trend and the minimum required generated power to verify the satellite is and will always be “power positive” during its expected lifetime. The major losses experienced by the solar array during the mission are due to UV degradation and micrometeorites, random string failure and radiation. In the frame of the lifetime analysis the min. of the Solar Arrays currents of each year is, then, compared to the minimum value observed during the first year of spacecraft life to estimate the degradation factor. The minimum of the Solar Arrays current is measured in July because of the maximum distance Earth-Sun along the year.

- Battery Degradation: the calculated Power of Discharge increase with time is compared against the expected trend to verify it can always provide the required power during the satellite expected lifetime.
  In particular, the degradation over the unit lifetime leads to lower cell voltages when discharging the battery at the same Wh and at the same load. This means that, at some point in time the degradation may cause that the cell voltages during an eclipse will become too low to still guarantee enough power to cover the satellite demand without triggering any FDIR.

- Propellant Consumption: the consumption of propellant of the propulsion system is tracked, verifying the presence of margin with respect to the required amount for the handling of the remaining mission phases.
  In particular the amount of propellant that it is available at launch shall be enough to:
    - Bring the satellite from the injection orbit at launcher separation into the operational target slot.
    - Perform the manoeuvres required to keep the satellite within its predefined box in the constellation. In principle, the Galileo Orbits are designed in such a way that a single orbit-keeping manoeuvre per S/C lifetime is required.

  - Perform relocation manoeuvre, e.g. have the capability to move the spare satellite from the spare slots into its nominal slot for constellation management purposes.
  - Perform repositioning manoeuvre for constellation management purposes, e.g. the satellites may be redistributed in an orbit plane to amend a faulty nominal satellite when no spare satellite is available in that plane
  - Dispose the spacecraft into the Galileo graveyard orbit at the end of its lifetime to minimize the risk of collision with the operational constellation.
  - Perform Collision Avoidance manoeuvres with space debris in case of need.

- Reaction Wheels (RW) Trending: The reaction wheels are AOCS actuators that maintain and/or change the attitude of the satellite without impacting its position or disturbing its orbit. The nominal attitude can be maintained with a minimum of three healthy reaction wheels. Four reaction wheels are mounted on each Galileo satellite for reliability. The nominal lifetime of the wheels is 15 years in orbit. In the frame of the lifetime analysis the trend of RW Friction Torque against Speed is analyzed to identify possible outliers which might indicate out of nominal RW behaviors, leading to a potential issue as RW cage instability phenomenon. In particular, the torque the motors need to provide to the wheels to maintain their motion against friction and other non-conservative forces (i.e., the difference between the commanded torque and the actual torque applied by the wheels to the satellite) is used to monitor the performance of the wheels. Additionally, it is a function of the wheel speed, of the internal oil distribution and of the unit's internal temperature, and it is expected to increase with the increase of the wheels' speed. For this reason, the observation of an increasing loss torque at given speeds would signal a degradation of the wheels' performance and, in consequence, could indicate a negative trend of the lifetime of the units.

- Gyro Lifetime Calculation:
  - In FOC spacecraft the Gyro is used for the propagation of the yaw angle when the sun is not in the Fine Sun Sensor field of view and for the propagation of the roll and pitch angle when more than one channels of the earth sensors is blinded by a celestial body [5]. In order to be sure that there is no limiting factor on the gyro the accumulated on-time and number of cycles of each unit for each spacecraft is calculated and compared against their maximum allowed values by design, to identify if these numbers are reached before the satellite expected lifetime leading to the need to develop ad-hoc strategy.
  - In IOV spacecraft the gyro is only used during manoeuvres or in case of reconfiguration into safe mode or intermediate safe mode due to FDIR mechanisms. Anyway, they are switched on once per years as part of the yearly maintenance activity and the source current evolution with time coming from in-flight measurement is compared versus the predicted worst case by design.

- Galileo Atomic clocks: The atomic clocks on the Galileo satellites present parameters that have an expected drift with time. Once this drift reaches a certain threshold, actions need to be performed. The atomic clocks are considered as life limited units since they are fundamental for the service provision. If no atomic clock is available anymore on-board a satellite, the satellite health, commandability and manoeuvrability is not endangered, however the spacecraft cannot provide navigation service.
  - PHM Lifetime Trending: the trend of PHM key parameters is analyzed since the satellite BOL to identify out of family behaviors. Additionally, the yearly drift of the main key parameters is compared with the expected threshold provided by the unit manufacturer to identify any potential anomalous behavior.
  - RAFS Lifetime Trending: the trend of the RAFS key parameters is analyzed since satellite BOL to identify out of family behaviors.

- Galileo RF subsystem (only for FOC satellites): the drift of the Travelling Wave Tube (TWT) Anode Voltage since first turn on is calculated and compared against the expected worst-case curve provided by the unit manufacturer, to identify possible out of family behavior and potential performance degradation reached within the satellite expected lifetime. The drift of the TWT Helix Current since first turn on is calculated to identify outliers respect to the others spacecraft.

4.2 Report preparation and process description

The first step for the preparation of the Lifetime Analysis is the identification of the relevant parameters from the existing telemetry database. The selected telemetry is processed to create long-term plots that show the evolutions with time of the specific parameters since first switch-on. Additionally, when needed, a data interpolation is also executed to perform the trend analysis.

In particular, for the few units that have serial TMs scripts are used to decouple the TM of the A unit from the B unit in order to plot the behavior of the two units separately. For the parameters in which a decreasing or increasing trend is visible the script are also used to forecast when the threshold will be reached and in order to assess the rate per year the TM parameters is changing. These values are compared with the expected one provided in the S/C user manual and if any issue is identified an ad-hoc analysis and assessment is done to identify the root cause of the deviations.

In other cases, like for the RWs, the scripts are used in order to plots one TM parameter against the other in order to assess if there is any criticality.

On top of these analysis different scripts have been developed to plot the different spacecraft in a single plot and spot out-of-family behavior.

The update of the Galileo Constellation Lifetime Analysis is nominally performed on a yearly basis. The reason behind it is that the telemetry trends identified in the frame of the Lifetime Analysis are nominally not expected to vary throughout the year. However, there are special events that could lead to the necessity of updating the Lifetime Analysis. In these cases, the impact on the lifetime prediction will be assessed and reported, if meaningful and deemed necessary, an ad-hoc release can be executed.
These special events may include:

- Change in unit usage strategy
- Spacecraft anomalies, detected in the frame of the daily monitoring or in the frame of the weekly and monthly spacecraft performance report
- Major on-board software upload campaign (including changes in the agreed upload plan)

4.3 Statistical analysis of failure

4.3.1 Calculation of statistical failure figure using in-orbit data

The accumulated-on time of the flying spacecraft for FOC and IOV families is computed in order to calculate the mean-time-to failure (MTTF), the failure in time (FIT) and the reliability figure based on in-orbit data.

The MTTF is defined as the average time-to-failure (1):

$$MTTF = \int_0^\infty t * f(t)dt \qquad (1)$$

The MTTF, even it is an index of reliability performance, does not give any information on the failure distribution of the component in question. Because vastly different distributions can have identical means, it is unwise to use the MTTF as the sole measure of the reliability of a component.

The easier way to calculate the MTTF, during the design phase is the following one (2):

$$MTTF = Ttest / Nfailure \quad (2)$$

A similar approach is used in order to estimate the MTTF of the different units of Galileo spacecraft based on the available accumulated on-time and the observed failure.

The failure rate λ is defined as the number of failures occurring per unit time. It represents the numbers of failures that occurs in 10^9 hours as can be seen in the following equations (3):

$$FIT = \frac{10^9}{MTTF} \quad (3)$$

For cold redundant equipment a dormancy factor can be considered, assuming that units that are not powered have a lower failure rate than active units. Usually, a dormancy factor or 0.1 is applied.

Additionally, for active equipment which are not expected to be used throughout the orbital lifetime (e.g. gyro) a duty cycle DC can be considered (4).

$$DC = \frac{operating\_time}{mission\ duration} \quad (4)$$

The reliability of the unit it is defined as an exponential function (5)

$$r(t) = e^{-t/_{MTTF}} \quad (5)$$

The reasons why the exponential distribution has been chosen can be found hereafter:

- it presents some limitation in modelling the early failure after launch, but it is quite good to model the increase of failure rate experienced by units towards EoL.
- It is one of the most widely used in the space sector and compared to others common distributions (e.g. Weibull) is quite easy to model as it requires only one parameters (λ).

Due to the limited amount of failure and the limited accumulated in-flight on-time, the possibility to adjust the MTTF considering the in-orbit experience is considered relevant only for the units in which the number of failures is statistically relevant.

4.3.2 Statistical distribution of failure over different mission phases

The failure rate function measures the conditional probability that a failure of a device occurs, knowing that this device has been well-functioning up to time t or later. Experience has shown, especially for electronic systems and components [6], that the curve representing the failure rate as a function of time t, has the general "bathtub" shape (see fig.3)

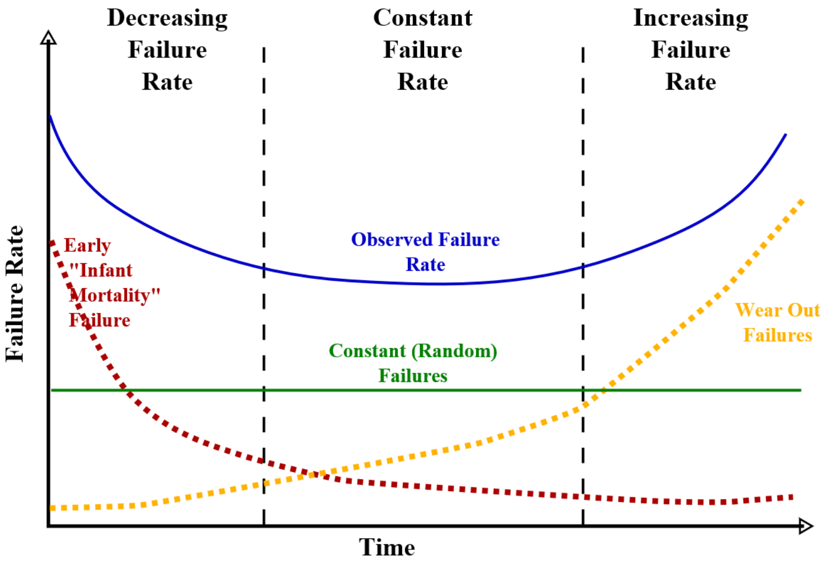


Fig. 3. Bathtub failure distribution

The curve identifies three regions:

- Phase 1: “Infant Mortality” Failure – Decreasing Failure rate: The failure rate is usually high at the beginning of the life of the item. This can be explained by undiscovered defects and/or design flaws that cause the premature termination of the items (infant mortality). These failures show up when the items are activated. The failure rate decreases rapidly with time. This behaviour can be explained by the progressive elimination of defects due to poorly controlled design or manufacturing processes that make the items as less likely to fail when the survival time increases, as demonstrated by electronic devices during their early life or the burn-in period.

- Phase 2: Constant (Random) Failures: The second phase defines the useful life period, which is generally very long. Once the item has survived the infant mortality period, it stabilizes at an approximately constant level during the operational life (constant failure rate). The failures are said to be random. Their appearance is not related to the age of the component but to other mechanisms of damage. Predictive reliability calculations are almost always performed in this useful life and the choice of the exponential law for reliability, the main property of which is to be without memory (i.e. item is as good as new), is quite satisfactory. At the end, it rises when wear-out and aging become dominant.

- Phase 3: Wear -Out Failure - Increasing Failure Rate: The last phase is the aging period, characterized by irreversible physical-chemical phenomena leasing to a progressive deterioration of the device so that it ages or wears out. This leads the item to exhibit an increasing probability of failure with time and its failure rate increases correspondingly. For an electronic component, this period is usually much beyond the nominal lifetime.

A screening of the anomaly opened for the Galileo Constellation is executed to distinguish how the different failure can be distributed in the bath-tube shape and mainly identify if there is any anomalous behaviour that can be linked to phase 3. In particular, the goal is the identification of possible ageing effects that can lead to higher sensitivity of some specific unit to radiations or other external factors for which the implementation of mitigation action, such the fine-tune of the FDIR setting, may be needed in order to avoid unnecessary reconfiguration

It worth to mention that the possibility to observe in-flight failure due to ageing effect is still limited as the majority of the satellite in orbit are still far from their nominal end of life.

Being Galileo a constellation of spacecraft the screening of the ARs opened in the different mission phases can also lead to lessons learned to be implemented in the design on the future satellites.

It is also considered relevant to identify failure observed right after a launch and related to any changes on manufacturing process, unit´s components, or to issue on production batches to identify in advance the anomaly that may be encountered on the upcoming launches and implement lesson learnt, work-around and mitigation action in due time.

4.3.3 Identification of Platform critical list Items.

Following ECSS-Q-ST-30-02C a tailored FMEA analysis of a possible double failure for all the platform units has been done to identify the critical items that requires ad-hoc discussion once the single point of failure is reached.

In particular the systems reliability of each unit assembly is calculated considering how the units are connected (e.g. k-out-of-n parallel configuration as for the RWs or simple parallel configuration as for the majority of the units in which there is a nominal and redundant ones)

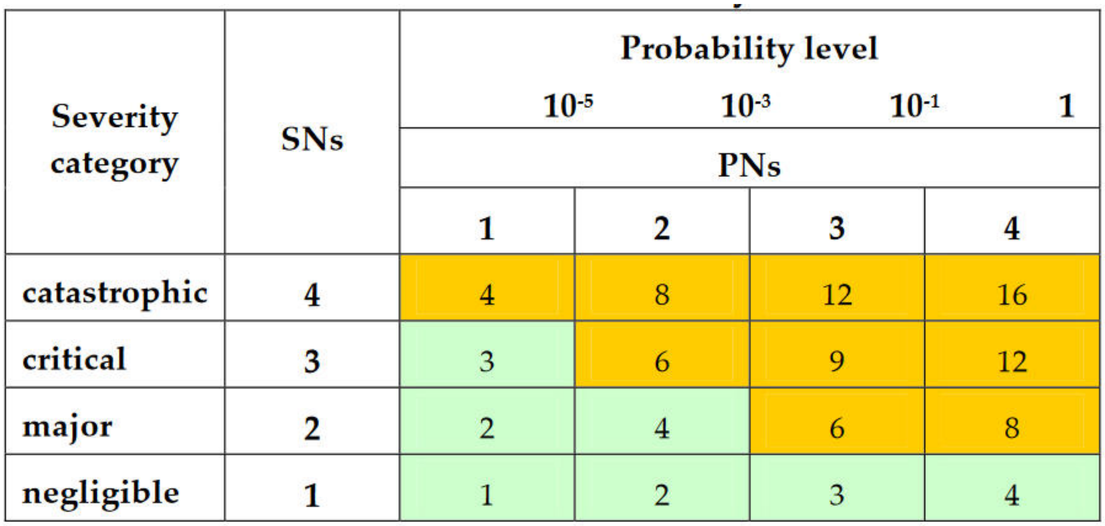
The probability of failure is calculated as follow (6):

$$p(t) = 1 - r(t) \qquad (6)$$

Being the reliability a function of time the same property applies for the probability of failure - so the value has been calculated assuming 12 years as a time reference. As for ECSS standard [7] this is needed to identify the probability number 1-4.

The severity number has been assigned considering the effect of a double failure: 4 is assigned when the double failure may prevent the capacity to dispose the S/C or even to command the S/C in some cases, 1 is assigned to units in which a double failure may not even prevent the capacity to use the spacecraft for service provision, 2 and 3 are assigned where there may be the possibility to develop ad-hoc strategies to at-least dispose the S/C after the second failure.

This approach is following the ECSS standard definition in which 1 is negligible, 4 catastrophic and 2 and 3 are respectively major and critical. The criticality matrix has been calculated as Probability number x Severity number as for ECSS standard.



Severity category	SNs	Probability level			
		10^{-5}	10^{-3}	10^{-1}	1
		PNs			
		1	2	3	4
catastrophic	4	4	8	12	16
critical	3	3	6	9	12
major	2	2	4	6	8
negligible	1	1	2	3	4

Fig. 3. Criticality matrix [7]

In this way, in case of HW failure affecting any units of the Galileo spacecraft it will be possible to identify the possible impact as for criticality matrix respect to the possibility to command or manoeuvre the spacecraft in the unlikely case of a double failure.

A risk assessment can be performed to consider the reliability of the unit for the cases for which the commandability of the spacecraft may be compromised in case of double failure.

In the cases in which an ad-hoc strategy is needed to handle a double failure, it will be necessary, as soon as the single point of failure for a critical unit is reached, to define ad-hoc strategy and procedure, outside the spacecraft design baseline to still guarantee the possibility to dispose the spacecraft in the graveyard orbit and also highlight any need of waiver respect to the international requirements for space debris mitigation.

5. Conclusion

The main outcome of the lifetime analysis it is to provide an overview of the status of the different spacecraft of Galileo Constellation, highlight any possible risk, when applicable, that some unit may fail before their nominal end-of-life.

At the same time, the lifetime analysis may suggest that some spacecraft can still be used beyond the nominal end-of-life. This is valid as long as the single point of failure for the critical platform unit has not been reached, no lifetime limiting factor has been identified from the lifetime analysis and the spacecraft can still be used for service provision.

The Galileo lifetime analysis is used as input for the management of the constellation to target accordingly the orbital plane for the upcoming launches and plan, when needed, relocation manoeuvre.

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