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# Use of recursive model for EPS-Sterna constellation design

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## Abstract

EUMETSAT is operating a system of meteorological satellites that observe Earth's atmosphere and ocean and land surfaces – 24 hours a day, 365 days a year. EUMETSAT assesses opportunities for further contributions to the realisation of the Vision 2040 of the World Meteorological Organization (WMO) Integrated Global Observing System through additional observation capacities and capabilities complementing the MTG and EPS-SG systems for the remainder of their planned lifetime. These opportunities include a constellation of small satellites called EPS-Sterna, expanding the EPS-SG microwave sounding capacity, for providing frequent soundings for Nowcasting at Arctic latitudes not covered by MTG observations.

The use of the recursive model for EPS-Sterna constellation design will allow to demonstrate compliance with mission availability end to end requirement (coming from users), while optimizing the use of the space assets via comparison analysis for:

- Initial Launch. Either single or dual launches are considered for initial deployment phase,
- The replenishment phase. The replenishment strategy for the constellation is driven by the satellites' design lifetime and reliability and has been conceived to ensure the required system availability throughout the thirteen years planned minimum mission lifetime. The approach above will be implemented by dynamically adapting the replenishment launch dates based on the health of the satellites in operation,
- Number of spare satellites on ground. Spare satellites are necessary to cope with satellite or launcher failures,
- Satellite manufacturing rate. The satellites production chain shall enable replenishment while minimising the satellites storage time on ground.

After the EPS-Sterna system model establishment and validation, several analysis have been performed to compare different configurations with the following main outputs:

- Mission predictive availability vs time,
- Number of satellites needed during the mission lifetime and the associated manufacturing rate,
- Number of launchers needed during the mission lifetime.

Thanks to these different analysis and comparisons, conclusions were drawn concerning e.g. dual vs single launch, relaunch policy and associated criteria for relaunch, which enabled EUMETSAT to identify the constellation design and the deployment and replenishment strategy which allow the most efficient use/allocation of assets and resources

**Keywords:** constellation, recursive model, space asset optimization

## Nomenclature

This section is not numbered. A nomenclature section could be provided when there are mathematical symbols in your paper. Superscripts and subscripts must be listed separately. Nomenclature definitions should not appear again in the text.

## Acronyms/Abbreviations

Calibration/Validation (Cal/Val)
ESA Artic Weather Satellite (AWS)
FengYun-3 (FY-3)
Launch and Early Operations Phase (LEOP)
Metop-Second Generation (Metop-SG)

Model-Based Safety Assessment (MBSA)
Monitoring and Control (M&C)
National Oceanic and Atmospheric Administration's Joint Polar Satellite System (NOAA JPSS)
Numerical Weather Prediction (NWP)
Proto-Flight Model (PFM)
System In Orbit Verification (SIOV)

## 1. Introduction

This paper presents an operational application of using recursive model to demonstrate compliance to an end-user mission availability requirement which is one of the driver requirements for the design of EPS-Sterna constellation.

It gives some insights into the model developed and used in EUMETSAT, as well as the overall decision-making process. Furthermore, this paper presents the EPS-Sterna constellation and examples (an example on the choice regarding number of satellites per launchers and another one regarding criteria for replenishment policy) considered when applying this method (and model) to design options decision.

## 2. Recursive Model Presentation

The EPS-Sterna constellation, made of several identical satellites, is quite complex to model regarding availability point of view, as a combination of random failures and deterministic thresholds.

Reliability Block Diagrams or Fault Trees, the usual methodologies that can be used for computing system availability, are not suitable for such a complex system. Therefore, the Markov Chains methodology is used instead, but in this case, the system model could still be complex.

The MBSA principle, via the AltaRica language, is a good solution to satisfy all the listed constraints. AltaRica is able to model each element of the system (e.g. each spacecraft) independently and then allows the system modularity. This kind of language is therefore able to model the system dynamic and to describe the way failures are propagating inside the system.

With the AltaRica language, each element is depicted by a block with a state-machine (Fig.1). The outputs depend on the state of the state-machine and input figures. The state-machine depends on the event that can impact the block. AltaRica allows to define an event by a probability law (e.g. in case of random failure) or a deterministic event (e.g. end of defined operations duration).

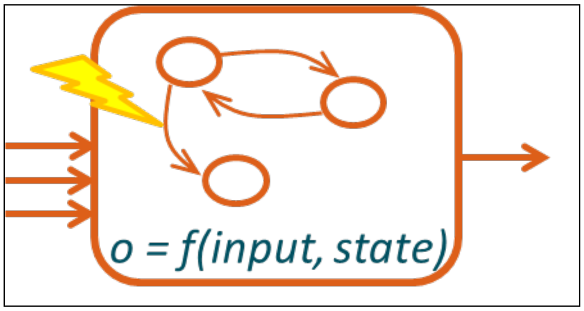


Fig. 1. Elementary Blocks depicted with AltaRica language

It's possible to link different elementary blocks between them in order to define the complete system to be modelled and analysed (Fig. 2).

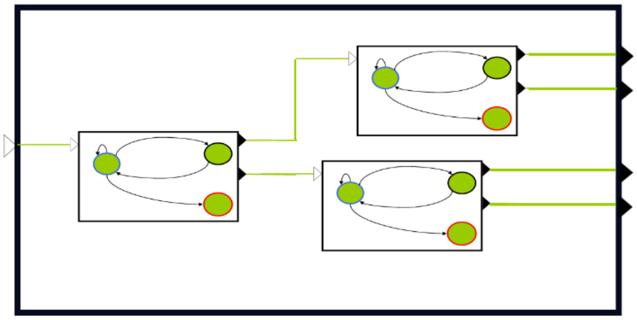


Fig. 2. Complete system with different elementary blocks

For the computation, the model is based on the principle that the system behaviour is described by specific availability curves between two moments of time, corresponding to either random changes in system state (in the case of random failure for example), or crossing over defined thresholds (e.g. satellite re-location or satellite end of life). The characteristics of the availability curves in that period of time is function of the specific assumptions that are valid between these two moments (e.g. number of satellites available, residual scanning capacity for specific missions, status of certain elements/sub-systems). As a result, the mission availability vs timeline is a multi-segment curve.
Therefore, a stochastic simulation based on Monte-Carlo is performed and at the end of each simulation, the value of so-called observers (in our case the EPS-Sterna mission availability per month) is computed.

## 3. EPS-Sterna constellation presentation

The objectives of the EPS-Sterna mission are:
- to complement the microwave observations from the Metop-SG and NOAA JPSS polar-orbiting, meteorological satellites;
- to contribute to improved global and regional NWP accuracy, including Nowcasting at high latitude and over the Arctic region;
- to increase the frequency and availability of microwave observations;
- to contribute and support climate monitoring.

The primary products identified to be necessary for NWP and NWC which shall be delivered by the EPS-Sterna Mission are:
- Water-vapour profiles in clear and cloudy conditions,
- Temperature profiles in clear and cloudy conditions.

The frequent availability of detailed temperature and moisture soundings would also contribute to fulfil other key requirements common to Nowcasting and Very Short Range Forecasting (VSRF) at regional scales such as cloud microphysical structure.

To meet these objectives, the EPS-Sterna system consists of a constellation of small satellites providing passive microwave soundings of the atmosphere and ground segment for M&C and data processing, archiving and dissemination. The mission lifetime of the system will be greater than 13 years and each satellite will be designed for an operational duration longer than 5.5 years.
The EPS-Sterna satellites are based on the ESA Artic Weather Satellite (AWS) Proto-Flight Model (PFM) satellite that is flying on a Sun-Synchronous Orbit (SSO) at an altitude of 595km altitude. The EPS-Sterna satellites will fly on SSO with the same reference altitude at 3 different orbital planes: 15:30, 19:30 and 23:30 local time at ascending node (LTAN).

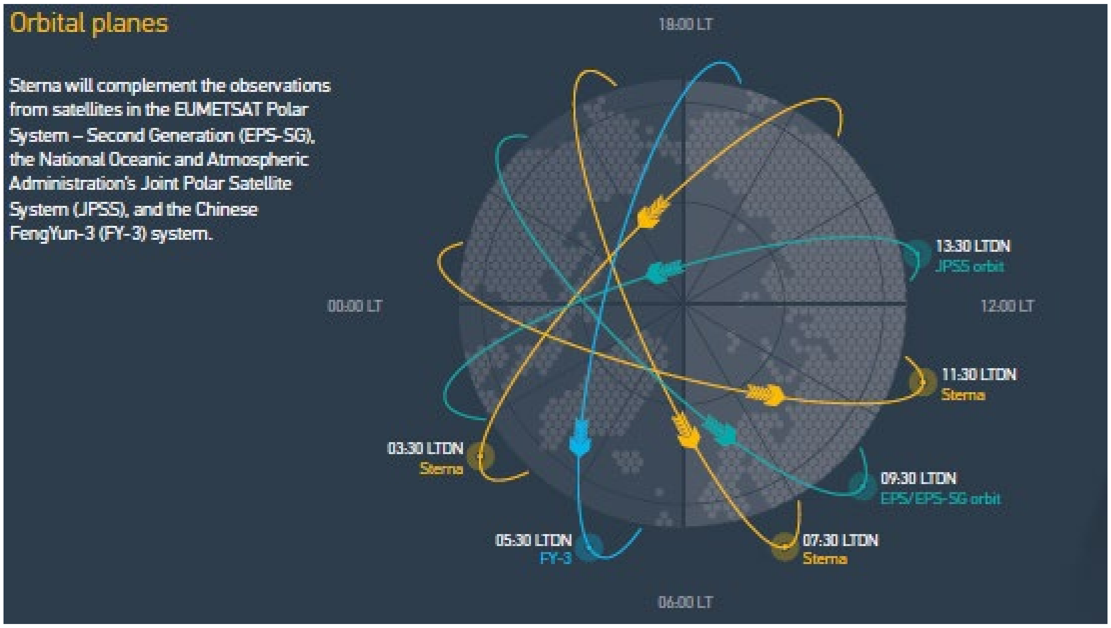
The EPS-Sterna satellites will be deployed in three different sun-synchronous orbital planes, chosen to be complementary to EPS-SG, JPSS satellites (LTDN 03:30, 07:30, 11:30) and Chinese FY-3 satellites, as well as to maximise the constellation performance in terms of "time to achieve 90% global coverage" (Fig.3).

The initial nominal configuration will consist of a total of six satellites in three orbital planes with two satellites per each plane, flying at an altitude of about 595 km. The satellites will be replenished by time to span a mission lifetime over 13 years.

Each satellite is specified for a nominal lifetime (including LEOP/ Orbit Transfer, 6 months in total) of 5.5 years. The possibility to extend the satellite nominal lifetime to 7.5 years is also in place. If a satellite is able to deliver mission products during the lifetime extension period, it will be considered as operational. On the other hand, these satellites are not imposed by strict performance requirements (e.g. timeliness, availability).

The constellation will achieve frequent revisit times. Considering the six satellites configuration, the mean time between observations on any area on Earth will be varying between 20 minutes and 3 hours, depending on the latitude.

At the time being, the first launches are planned for 2029, and therefore the end of mission is planned for 2042.



Sterna will complement the observations from satellites in the EUMETSAT Polar System – Second Generation (EPS-SG), the National Oceanic and Atmospheric Administration's Joint Polar Satellite System (JPSS), and the Chinese FengYun-3 (FY-3) system.

Fig. 3. EPS-Sterna Orbital Planes

## 4. Presentation of recursive EPS-Sterna constellation model

For the estimation of the EPS-Sterna mission availability vs time, a dedicated model has been built accordingly with basis defined in §2. This model has three main high-level inter-linked sections, i.e. the orbit section, the launch control section and the mission estimation section (Fig.4)

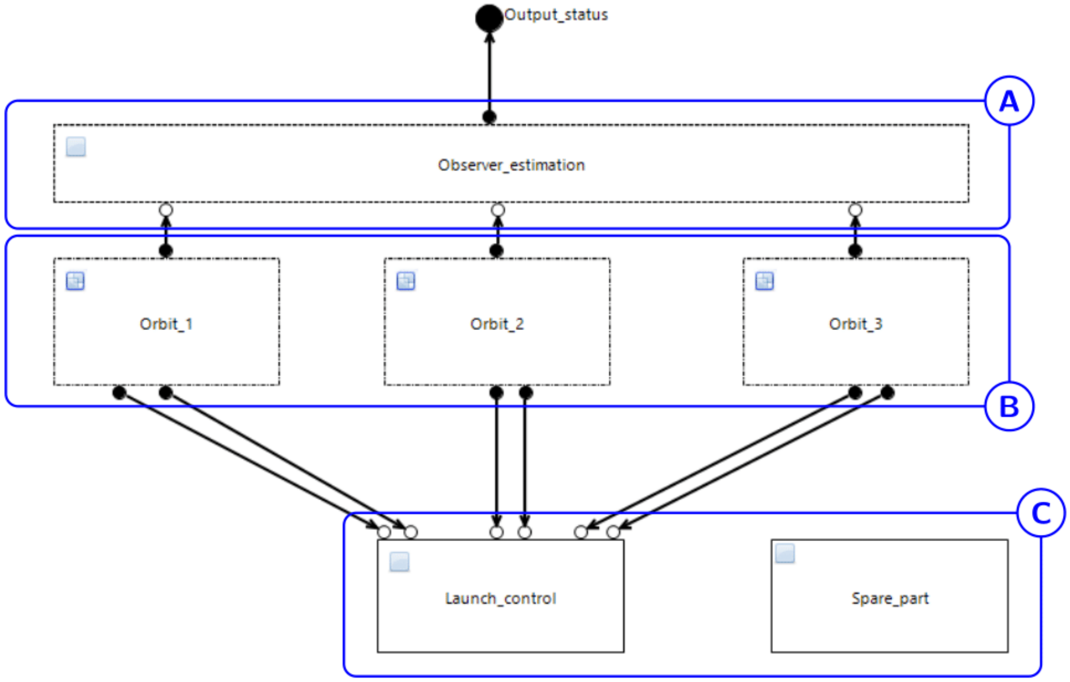


Fig. 4 EPS-Sterna MBSA model – Mission estimation section (A), Orbit section (B), Launch control section (C)

(A) The role of the "Observer_estimation" block is to assess if the minimum requirements for a successful mission are met and provide this information as a "nominal_failed" status on the "Output_status" connector.

(B) The role of the Orbit section is to provide the number of operating satellites and the number of orbiting satellites on each orbital plane.

The orbit section contains three independent "Orbit_n" blocks that operate identically. These three blocks is modelling the three different sun-synchronous orbital planes discussed in the §3.

(C ) The main role of the launch control section is to set up launch authorisation. The launch authorisation allows to start a launch process based on the:

- Launch and relaunch policy,
- Satellite availability in the storage.

The launch control section also manages the number of stored satellites and the continued satellite production.

As this model is built to support decision-making regarding the design of the constellation, the following elements have been defined as variable parameters with possibility to modify the value:

- Spacecraft reliability,
- Number of satellites embarked per launcher,
- Launcher success rate,
- Replenishment policy (rules for relaunching a S/C),
- Number of satellites manufactured and pace of manufacturing,

The following parameters are currently considered as not modifiable for the analysis:

- Minimum space segment configuration. The configuration [2,1,1], [1,2,1] and [1,1,2] is considered as the minimum to ensure mission required performance,
- 6 months for satellite commissioning (i.e. LEOP, SIOV, orbit transfer and Cal/Val),
- Satellite lifetime assumptions of maximum 7 years after commissioning,
- The mission lifetime is 13 years,
- The duration between decision to relaunch and effective launch is 12 months after a failed S/C,
- Number of satellites are constrained by 18 + 2 spares, accordingly with the current satellite manufacturing planning. The pace of satellite manufacturing is also defined.

## 5. Presentation of performed analysis and results

The ultimate goal of using the recursive model is to select the EPS-Sterna constellation architecture in compliance with the user required Mission Availability, i.e. to decide between several options of design the one which provide the compliant mission availability during the complete mission lifetime.

In this paragraph, we're presenting 2 examples of parameter which have been analysed for decision-making:

- For the launch of the first 6 satellites (constellation establishment), what is the better configuration: to launch 2 satellites per launcher or one satellite per launcher. This analysis is interesting in the context of launcher market with several new actors coming.
- For the replenishment policy, what is the better rule: to relaunch a satellite when nominal spacecraft lifetime (5.5 years) or when extended satellite lifetime (7.5 years) is reached. This analysis should be interesting as the reliability of small satellites as EPS-Sterna is significantly lowest than regular reliability of satellites operated usually by EUMETSAT (due mainly to less redundancies at platform level).

In the framework of these two analyses, the following assumptions have been defined:

- Satellite reliability = 0.55 after 5 years of Operations
- Satellite lifetime assumptions of maximum 7.5 years including LEOP and orbit transfer phase,
- The constellation will become operational at the end of T0+9 months, following completion of LEOP/SIOV/Orbit Transfer/Cal/Val phases of each satellite in the constellation.
- Replenishment launches (after the constellation establishment) will be done by adding one satellite which imposes single satellite launches.

### 5.1 Dual vs single launch analysis

For this analysis concerning the first 6 satellites, we're comparing 2 options:

- Option1: 1 launcher is carrying one spacecraft, launch to be performed every 2 weeks
- Option2: 1 launcher is carrying 2 spacecrafts; the setup is to have 2 months between the first two deployment launches and 1 month between the second and the third launch

For each of these 2 options, 2 different "launch probability of success" have been also analysed, 0.95 and 0.87, which respectively represents to a certain extend the probability of success for mature launchers and for newcomers' launchers. These figures will obviously evolve considering the heritage data available with the increasing number of planned launches.

For this comparison, the replenishment policy is to relaunch when nominal spacecraft lifetime is reached.

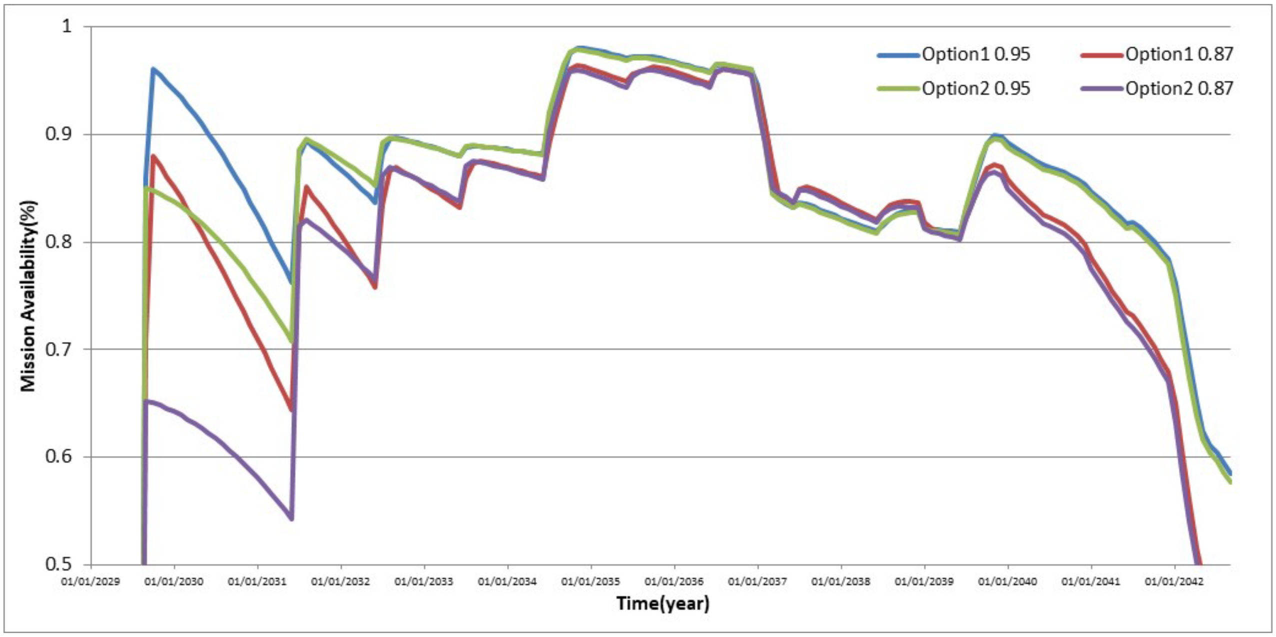


Fig. 5. Dual vs single launch option vs mission availability

The results of the simulation (see Fig. 5) show that theoretically having six single satellite launches for the deployment instead of three dual satellite launches increases the overall mission availability. In this case the possible scenario is to perform six launches in every two weeks to keep the total duration of finalising all deployment launches in 3 months. It should be noted that this simulation has the only purpose to illustrate the capability of the EPS-Sterna MBSA model and exposes only one of the many aspects to be considered when selecting the launcher provider for the constellation and does not exclude the use of dual satellite launchers for EPS-Sterna as other consideration are equally important for the selection (e.g. launcher readiness, reliability, cost etc.).

### 5.2 Replenishment policy analysis

In all the mission availability curves (see example in the previous paragraph), it should be noted that during the year 2035 and 2036, the mission availability is very high. A contrario, during the last year, the year 2042, the mission availability dramatically dropped.

To improve the probability for delivering the mission during the overall mission lifetime (i.e. in short flat the year 2035 and year 2036 high probability in order to increase low year 2042 one), the rule concerning the relaunch has been amended considering the extended spacecraft lifetime instead of nominal spacecraft lifetime.

Therefore,

- In case of launch failure, a new launch is planned with the same number of spacecraft,
- In case of spacecraft failure before end of its lifetime, a new launch is planned if [1 2 2], [2 1 2], [2 2 1] configuration is not achieved,
- When a spacecraft is reaching a defined operations duration (Option1 5.5 years nominal lifetime, Option2 7.5 years extended lifetime), a new spacecraft is launched (and then 6 months of commissioning before being operational).

It should be noted that the analysis was conducted by increasing the spacecraft defined operations duration 6 months by 6 months, from 5.5 years to 8 years. The best average mission availability was reached with 7.5 years, which is the extended spacecraft lifetime. The curves are depicted in Fig.6.

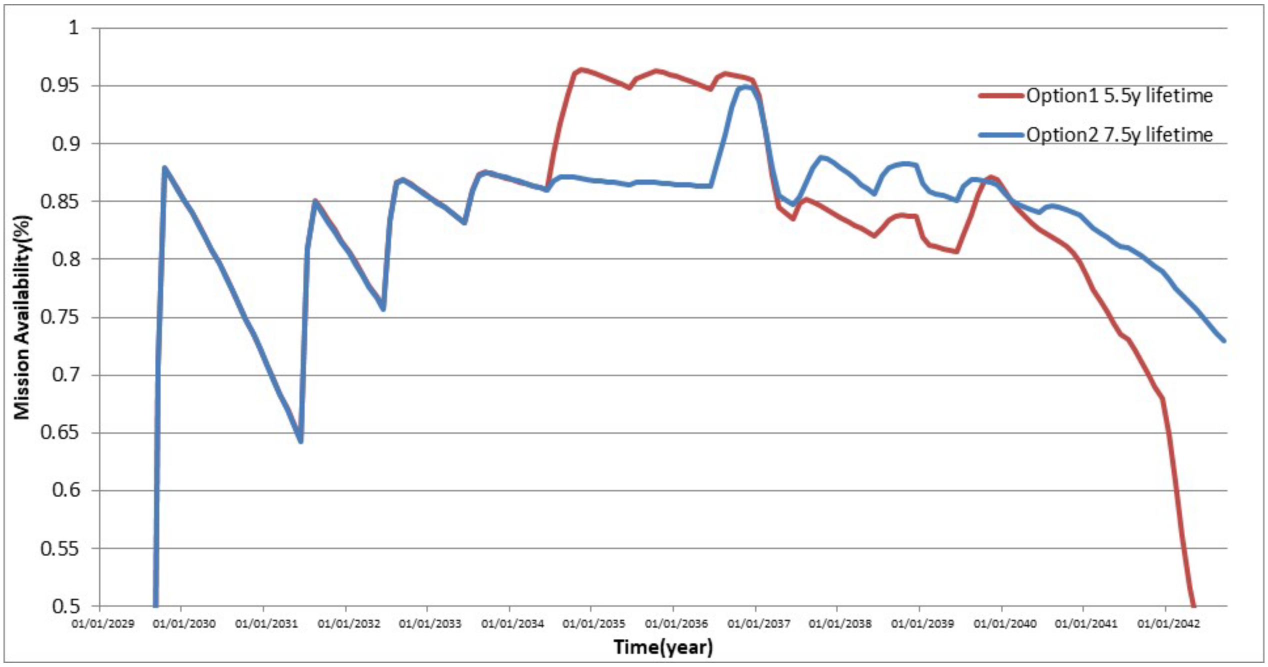


Fig. 6. Replenishment policy comparison

As an example, the comparison is performed considering that one launcher is carrying one spacecraft, and the launch success rate is 0.87.

The model allows to populate the comparisons for the complete list of variable parameters listed in Paragraph 4 to observe the impacts on the mission availability aspect. Therefore, this powerful tool can continuously support the design activities to monitor the compliance status against the mission availability.

It should be noted that:

- We can mix different options for different parameters,
- We are able to add financial figures for e.g. cost of launcher, cost of satellite, cost of one year operation…for establishing the total cost of mission, allowing to add the financial dimension in addition to the technical one.

## 6. Conclusions

Based on the above elements, among which the results of the recursive model play an important role, the Programme is able to define a valid EPS-Sterna constellation design wrt mission availability.

The modelling has proven to be very useful to EUMETSAT, allowing to analyse and establish a strategy for satellites deployments and replenishments and in the future could be used during operations to maximise the use of space assets.

## Appendix A EUMETSAT Presentation

EUMETSAT is the European Organisation for Exploitation of Meteorological Satellites (www.eumetsat.int).

The primary objective of the Organisation is to Establish, maintain and exploit European systems of operational meteorological satellites, taking into account as far as possible the recommendations of the World Meteorological Organization.

The Further objective is to contribute to the operational monitoring of the climate and the detection of global climatic changes (EUMETSAT is a world leader in providing the robust scientific data from space needed to understand climate variability and change. Our long-term, multi-satellite programmes provide an increasing portfolio of observations that are key contributions to climate monitoring).

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