14º WETE
Workshop em Engenharia e Tecnologia Espaciais

Continuous Verification during the Operational Life of Federated Satellite Systems

Pedro Ângelo Vaz de Carvalho [1], Fatima Mattiello-Francisco [2]

[1] National Institute for Space Research, São José dos Campos, SP, Brazil
MSc student in space systems engineering and management – CSE/ETE.

[2]National Institute for Space Research - CSE/ETE

pedroangelovaz@gmail.com

Abstract. *A Federated Satellite System is a dynamic system of systems where the number and operation of constituent satellites and ground stations change over time. Continuous verification of the concept of operation of the constellation during the operational lifecycle is necessary for understanding its current capabilities and better allocating the available resources. This paper introduces COSCAT (ConOps Satellite Constellation Analysis Tool), a simulator that supports stakeholders in analyzing the behavior of constituent satellites in an integrated and friendly way. Based on the properties of each element constituting the constellation in a given period, the simulator calculates the operation scenario of the entire system, expressing the impact of changes on the revisit statistics, ground station availability, and individual satellite resources. An example constellation with operation scenarios after modifications on the constituent systems demonstrates the use of the tool and analysis of the results.*

Keywords: Satellite; Constellation; Concept of Operation; Simulation; System of Systems.

1. Introduction

A constellation comprises two or more satellites with similar components and capabilities, working towards a common goal. A larger number of constituent systems means it is usually constantly changing, due to failures or the addition of new elements. For large constellations, years go by before all satellites are successfully inserted into their corresponding orbits, only to find some of them started failing or never worked in the first place, making for a constantly changing operation and hard to predict the exact configuration in the long term. The constant reassessment of the coverage with every modification is necessary to base the decision-making and resource allocation. According to Jakob et al. (2019), The consequences of failing satellites can be so relevant, even for constellations with hundreds of satellites, that many companies have spare satellites already in orbit to replace those missing. The author then proceeds to present a strategy to manage spare satellites and reduce replacement costs, which again shows the importance of having a clear assessment of the consequences of these changing systems.

According to Golkar and Cruz (2015), a federated satellite system (FSS) is a spacecraft network, usually from different operators and missions, trading unused or inefficiently allocated resources, attempting to enhance performance, cost-effectiveness, and reliability and space missions. While constellations are usually thoroughly planned from the beginning, with all constituent satellites and failure scenarios well known and planned for, an FSS can be considered a system of systems (BATISTA; MATTIELLO-FRANCISCO; PATARICZA, 2022), where each constituent satellite, which may even be a constellation, was independently developed, with its own mission requirements and concept of operation (ConOps), but that has available resource to join the federated effort on a common objective. Therefore, the system's independence and interoperability are a major factor when defining its behavior. These systems can have constituent satellites or entire constellations joining or leaving, individual satellites reducing the resources it will provide for the system, and failure of systems whose outcome is hard to predict because of too many scenarios and independent mission controls for each constituent system.

Therefore, the ability to quickly simulate the operation scenario of such systems is crucial to adapt the used resources and keep the solution optimal.

An overview of how the systems operate and interact with each other and the environment is a key factor for simulating the constellation and deriving relevant parameters. For that purpose, it is necessary to derive part of the concept of operation of the system, describing how data is collected and distributed, the communication between the system elements, and some of its internal behaviors (WERTZ et al., 1999). A full ConOps comprises more information, which is important for the mission design and development, but the described elements suffice for a continuous analysis of such systems.

For constellations with partial cover, the most important parameter is the revisit time, according to most works on the subject (ULYBYSHEV, 2008; HANSON; EVANS; TURNER, 1990). Other parameters can be important in the constellation concept of operation scope, like inter-satellite links, discussed by Cornara et al. (2001) and ground station availability. Additionally, in the scope of federated systems, individual satellite resources can influence its contribution to the system, making the internal battery and memory of the satellites analysis often needed.

The challenges imposed by a federated concept led researchers to work on means to better study and understand its dynamics. Grogan et al. (2014) developed a simulation architecture for a multi-stakeholder interactive simulation and a prototype simulation toolkit for demonstration and further developments. The architectures serve for a general purpose in FSS modeling and simulation, accepting increasing levels of detail, but with a focus on demonstrating uses mainly to understand cooperation in data capture and exchange between federates, aiding in the design of such systems.

Commercial simulators can also achieve similar results in obtaining cooperation effect between federates. Systems Tool Kit (STK) can simulate all sough results, like revisit times, ground station availability, and satellite resource budgets, considering data relay between them (SANAD; MICHELSON, 2019). High cost and setup time for such simulators can be a drawback for rapid continuous analysis, pushing back the decision time and increasing operational costs.

Considering the necessity for the continuous analysis of federated satellite constellations, COSCAT (ConOps Satellite Constellation Analysis Tool), a simulator prepared to deal with the mentioned parameters was developed. While it focuses on the concept of operation analysis and doesn't explicitly follow the architecture from Grogan et al. (2014), the tool defines most objects and parameters presented in the work, calculating the main outputs for quick analysis. Furthermore, having a specific objective in mind, the simulator is fast and intuitive to setup and cheap to operate, while still providing the effect of changes in an FSS or the potential contribution of a new actor in the system.

This paper's objective is to present the use of COSCAT simulator in the context of continuous verification of federated constellations and how to analyze the relevant outputs. The "Methodology" section introduces an overview of the simulator's required inputs and outputs and the simulated constellation and scenarios. The "Results and Discussion" section explains the most important results and their effects on the constellation. Finally, the last section concludes the paper with the final remarks and next steps.

2. Methodology

The simulation setup requires some key information on the Federated Satellite System. The propagation of the coordinates, and subsequent connections based on the position requires the orbit of the satellites, defined by Keplerian elements (WERTZ; EVERETT; PUSCHELL, 2011). The satellites further contain equipment objects and several configuration parameters, including battery and memory maximum and initial levels, power generation, data transfer rates, and connection rules to other elements. Ground station objects receive the data collected by the satellite, and ground element objects either send data to the satellite or represent a region of interest for revisit times evaluation. The configuration object finally gathers all these objects plus configuration parameters like simulation time and orbit propagator. A plugin is available to transform a model of the concept of operation into the simulation setup code, allowing for model integration and turning the whole process more intuitive and friendly.

The output contains detailed revisit statistics for every ground element in the simulation, with mean and maximum revisit times, mean connected time, percentage of connected time, and relevant standard deviations. For each satellite, simulation data is presented in time steps, like coordinates, battery, memory, and equipment status, allowing for further post-processing by the user. Finally, the visualization tool allows for a better graphical representation of these parameters.

The simulation is based on the information provided by the concept of operation, which is summarized in Figure 1 for the example federated constellation. In this hypothetical scenario, three constellations are collaborating to observe the Amazon rainforest with imaging cameras, which is not the original objective of the non-Brazilian constellations. Therefore, the three Chinese and German satellites are only sharing their unused resources to help with the effort, and their data collection capabilities on this effort might change depending on the needs of the main stakeholder or satellite failures. Furthermore, the Brazilian satellites in this joint effort can connect to the other ground stations, and the other satellites can connect to the Brazilian station.

Satellites in the same constellation are assumed initially identical. Internal components consume energy and gather data, like attitude control, onboard computers, and other instruments, while the power subsystem generates energy and the telemetry downlinks the internal data. These definitions allow the analysis of the satellite's internal battery and memory.

Five ground elements on the corners and the center of the Amazon rainforest represent the region of interest, which are used to track revisit times on each. The ground station connection percentage is also analyzed to check for the effect of conflicts between two satellites requiring the same connection simultaneously.

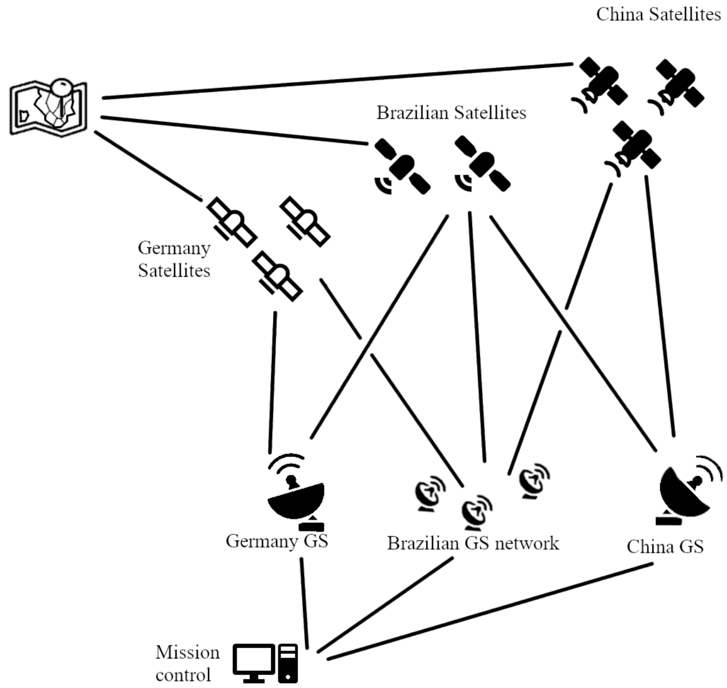

Figure 1. ConOps illustration for the example constellation.

The first simulation analyses the initial scenario, which fulfills the revisit times requirement, as a comparison basis for modifications that might occur in the constellation.

The second scenario considers China leaving the effort altogether because of the increased need for imaging on their primary stakeholder. The effects of this change are analyzed and acted upon, which results in the third simulation where Brazil manages to assign two other satellites to the imaging effort.

3. Results and discussion

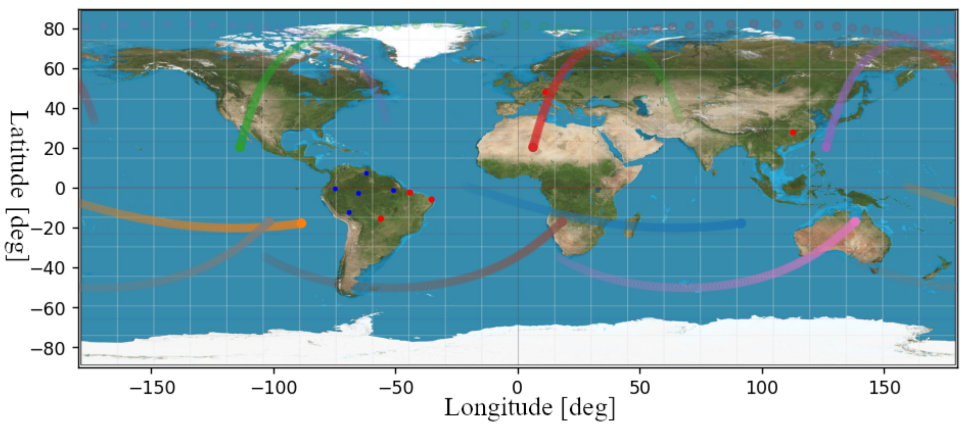

Figure 2. Simulation elements visualization.

The results of the first simulated scenario represent the initial condition of the federated system, capturing images from the Amazon Rainforest region. Figure 2 depicts the simulation elements in a specific instant. The red dots represent the ground stations, the blue dots represent the elements used for revisit time calculations in the Amazon region, and each dot with the trail exhibits the satellite path in orbit for a given period of simulation. .

The simulation of 20 days of operation resulted in the revisit times in Table 1, where the cardinal directions refer to the blue dots in Figure 2. We can assume the forest monitoring stakeholders desired a mean revisit time of 12h and a maximum revisit time of 48h. Being a federated system with changing budgets, the requirements cannot always be fully satisfied, but the results are close to the desired values. The conflict between satellites requiring ground station connection reduces the connected times an average of 4.5%. However, that is a lower value than the reduction resulting from no ground station cooperation, and less significant than the effect of the cooperation in the revisit times. Therefore, ground station availability is not a problem in this mission and needs no further analysis.

Table 1. Revisit times for the capture points in the first simulation scenario.

Captured element	Maximum revisit time [h]	Mean revisit time [h]
South	60.5	10.4
East	51.3	11.2
North	39.6	9.8
West	39.6	12.6
Center	35.1	10.4

It can also be noted in Figure 3 that the Chinese satellites captured data near their downlink capacity, meaning the data capture resource is at the limit for this satellite during the current operation. This limitation explains the second scenario where the Chinese satellites must abandon the federated effort to fulfill new operation requirements from the main stakeholders. It is also relevant to note in Figure 4 that Brazilian satellites are operating under their maximum capacity in terms of memory and battery. This valuable resource can be later used in regions other than the main objective of the satellites.

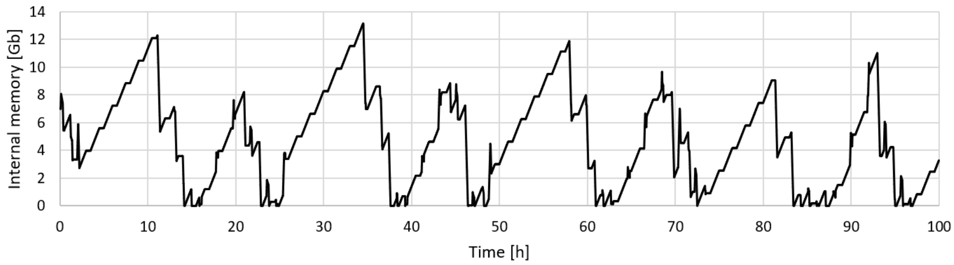

Figure 3. Internal memory over time of a Chinese satellite.

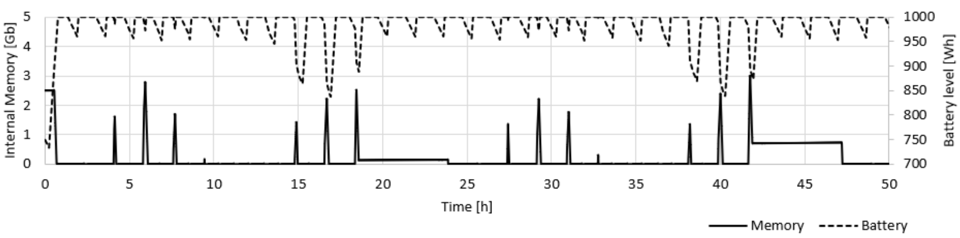

Figure 4. Internal memory and battery of a Brazilian satellite.

After China leaves the FSS monitoring the Amazon forest, the revisit times increase greatly, resulting in the values in Table 2. This increase will push mission operators to seek other satellites contributing to the FSS to bring the system closer to the stakeholder's needs.

Table 2. Revisit times for the capture points in the second simulation scenario.

Captured element	Maximum revisit time [h]	Mean revisit time [h]
South	122.86	15.48
East	117.46	19.19
North	162.29	15.47
West	94.15	19.99
Center	154.24	18.45

In this example, two Brazilian satellites from other imaging missions were assigned to observe the region and provide additional support for monitoring the Amazon Rainforest. With the operation of these satellites in the effort, the mean revisit times were brought back closer to twelve hours, while the maximum revisit times remained significantly higher than the desired values, even with a large decrease (Table 3).

Table 3. Revisit times for the capture points in the third simulation scenario.

Captured element	Maximum revisit time [h]	Mean revisit time [h]
South	58.35	12.30
East	107.87	14.99
North	76.86	11.70
West	77.16	14.54
Center	107.86	13.70

With these results and the final configuration of the FSS at the moment, the mission operators would remain searching for other satellites to join the effort, allowing for revisit times that fulfill the stakeholder's requirements and for the additional Brazilian satellites to return the full operation focus to their initial mission objective.

4. Conclusion

Simulations are necessary to ensure systems meet the requirements during the design and operation phases. This paper demonstrated the use of COSCAT for the continuous verification of Federated Satellite Systems, especially for evaluating the effect of system modifications on the relevant parameters and aiding the proceeding decision-making. The demonstration used a hypothetical scenario, exemplifying the simulator application on the verification steps and possible mission modifications deriving from the analysis. In real applications, mission operators will have predefined procedures to deal with the modifications and to evaluate the situation with the simulator.

The ease of simulator setup and the possibility to reuse most of the configuration with modifications on the FSS allows for changes to be evaluated within the hour in most cases, which allows for reduced operational costs and for quick decision-making when it is necessary.

Future works related to the development of the simulator include the creation of functions allowing for further detailed analysis of constellations. Possible relevant next additions include solar panels for the satellites, the possibility of data packets and communication protocols between elements, and the output of the full access times and gap results for each satellite.

Acknowledgments: *This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001.*

This study addresses the research subject related to INPE´s case study and to ADVANCE (Addressing Verification and Validation challenges in Future Cyber-Physical Systems) Project H2020-MSCA-RISE-2018-GA No 823788.

References

BATISTA, C. L.; MATTIELLO-FRANCISCO, F.; PATARICZA, A. Heterogeneous federated cubesat system: problems, constraints and capabilities. *arXiv preprint arXiv:2203.14721*, 2022.

CORNARA, S. et al. Satellite constellation mission analysis and design. *Acta Astronautica*, Elsevier, v. 48, n. 5-12, p. 681–691, 2001.

GOLKAR, A.; CRUZ, I. L. i. The federated satellite systems paradigm: Concept and business case evaluation. *Acta Astronautica*, Elsevier, v. 111, p. 230–248, 2015.

GROGAN, P. T. et al. Multi-stakeholder interactive simulation for federated satellite systems. In: IEEE. *2014 IEEE Aerospace Conference*. [S.l.], 2014. p. 1–15.

HANSON, J.; EVANS, M.; TURNER, R. Designing good partial coverage satellite constellations. In: *Astrodynamics conference*. [S.l.: s.n.], 1990. p. 2901.

JAKOB, P. et al. Optimal satellite constellation spare strategy using multi-echelon inventory control. *Journal of Spacecraft and Rockets*, American Institute of Aeronautics and Astronautics, v. 56, n. 5, p. 1449–1461, 2019.

SANAD, I.; MICHELSON, D. G. A framework for heterogeneous satellite constellation design for rapid response earth observations. In: IEEE. *2019 IEEE Aerospace Conference*. [S.l.], 2019. p. 1–10.

ULYBYSHEV, Y. Satellite constellation design for complex coverage. *Journal of Spacecraft and Rockets*, v. 45, n. 4, p. 843–849, 2008.

WERTZ, J. R.; EVERETT, D. F.; PUSCHELL, J. J. *Space mission engineering : the new SMAD*. Hawthorne, CA: Microcosm Press, 2011. (Space technology library ; v. 28). ISBN 9781881883159.

WERTZ, J. R. et al. *Space mission analysis and design*. [S.l.]: Springer, 1999. v. 8.