

# Introducing the European Space Agency Architectural Framework for Space-based Systems of Systems Engineering

Daniele Gianni, Niklas Lindman<sup>\*</sup>, Joachim Fuchs and Robert Suzic

*European Space Agency*

**Abstract.** System of Systems (SoS) engineering introduces a higher level of complexity compared to conventional systems engineering, for the number and geographical distribution of resources, and for interoperability and agreements issues, for example. In domains such as defence or Information Technology, architecting methodologies have been introduced to address engineering needs deriving from this increased level of complexity. From ongoing and future European space programmes, *ESA* has identified new engineering needs that cannot be addressed with existing methodologies. These needs concern the use of the methodology to support decision making, the representation of European regulation and policies, and the representation of space-specific domain concepts. In this paper, we introduce the *European Space Agency Architectural Framework (ESA-AF)*, an architecting methodology that aims to address these new engineering needs by improving on existing architecting methodologies. In addition, *ESA-AF* introduces exploitation tools for user-friendly interactive visualisation of SoS architectural models and for textual reporting of model data, enabling non technical users to exploit these models. We also briefly present example applications of *ESA-AF* in support of SoS engineering activities for the *Galileo* navigation, the *Global Monitoring for Environment and Security (GMES)*, and the *Space Situational Awareness (SSA)* programmes.

**Keywords.** SoS, ESA-AF, enterprise architecting, architectural framework, MODAF, TOGAF, space.

## 1. Introduction

The space systems capabilities of global access and remote sensing have contributed to the pervasive use of space systems to improve the quality of living by supporting the implementations of advanced services such as climate monitoring, disaster management or global telecommunication. New services are often demanded to further improve our living; however, available funding is limited, and therefore optimising the reuse of existing resources becomes necessary. Many of these resources were originally designed for purposes different from the provision of the new services. Moreover, these resources are often managed and owned by independent organisations. A number of new issues arise when aiming to integrate these resources in new configurations—namely Systems of Systems (SoS) configura-

---

<sup>\*</sup> Author for correspondence: niklas.lindman@esa.int, ESA/ESTEC, Postbus 299, NL-2200 AG, Noordwijk, The Netherlands

tions [1]—for the provision of a new service. For example, these new issues can concern interoperability—incompatibility of physical interfaces or different data interpretation; agreements—resource use and expected performance; SoS stability and evolution—contrasting objectives of the organisations involved in a SoS configuration, resulting in different life-cycles and life-spans of the associated systems; number of resource—SoS can be composed by a very large number of resources. These new issues can considerably increase the complexity of the engineering activities, and therefore they motivate the introduction of new methodologies to support design consistency, decision making effectiveness, and managing the increased complexity, in general. In domains such as defence or Information Technology (IT), architecting methodologies have been introduced to support the decision making of systems and programme managers in SoS engineering activities. However, the European space context is considerably different from the typical contexts in these domains, for the institutional role of the *European Space Agency (ESA)* and the unique characteristics of the space domain. As a result, the same methodologies do not entirely suit the new engineering needs that *ESA* has identified from the European space context. These needs, which inherently derive from organisational necessities for cost reduction, concern the use of the architecting methodology, the representation of European regulations and policies, and the representation of space-specific domain concepts. In this paper we introduce the *European Space Architectural Framework (ESA-AF)*, an architectural methodology aiming to address these needs while leveraging on the established methodologies *TOGAF* [2] and *MODAF* [3]. Specifically, *ESA-AF* introduces concepts for the representation of interface specifications, data policies, security requirements, and financial regulations, for example. Moreover, *ESA-AF* defines new analysis methods to guide the model definition and support issues identification and solution. *ESA-AF* consists of a software infrastructure and a set of business rules for the definition, maintenance and use of the architecting methodology.

The paper is organized as follows. The *European Space Context* section outlines the organisational and technical background motivating the introduction of *ESA-AF*. The *Needs for an ESA Architectural Framework* section presents the needs arising from the European space context. Following, the *ESA-AF* section describes the methodology, including the technical requirements and the framework structure. The *Example Application* section presents preliminary use cases of *ESA-AF* in support of the SoS engineering activities for the *Galileo* navigation [4], the *Global Monitoring for Environment and Security (GMES)* [5], and the *Space Situational Awareness (SSA)* [6] programmes.

## 2. European Space Context

The European characteristics of wide diversity of national cultures, regulations, and socio-economical directives introduce new political and technical challenges when aiming to implement increased capabilities and optimise resources at European level. Space systems can be financially very demanding and the most ambi-

tious types of programmes (e.g. Global Navigation Satellite System or Space Situational Awareness) can be delivered only through joint efforts, integrating available capabilities and reusing existing resources in SoS configurations. However, these configurations differ considerably from conventional systems as they are “*large scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal*” [1]. In addition SoS configurations present new properties (e.g. operational and managerial independence of the composing systems, evolutionary development, and geographic distribution [1]) that increases the complexity of the engineering activities compared to conventional systems engineering activities. To support SoS engineering activities, architectural models of SoS are an essential mean to support decision making as these models can be used to concisely provide comprehensive and consistent views on relevant facets of a SoS.

Within this context, *ESA* has the mission of promoting the cooperation among European states in space research and technology, for peaceful purposes, including the elaboration and implementation of activities in the space, the coordination of European and national space programmes, and the elaboration and implementation of industrial policies for space programmes [7]. To achieve its mission, *ESA* cooperates with European institutions to define space programmes and initiates new technologies and methodologies in support of systems design, development, integration and operation. Considering the increasing demand for new services with a space component and the respectively limited funding, the orchestration of European industry and national roles becomes a key issue for the effective implementation and provisioning of advanced space-based services. The European space context inherently shows the properties of the above defined SoS, where however the autonomy properties are further exacerbated for the inherent national influence and regulations constraining the degree of freedom of individual systems.

### 3. The Needs for an ESA Architectural Framework

In non space domains, architecting methodologies have been introduced to support system and programme managers in SoS engineering activities. For example, in the defense domain, *DoDAF* [8], *MODAF* or *NAF* [9], are the most prominent standard methodologies for SoS representation. Differently, *TOGAF* addresses more conventional IT architectures by defining an architecture planning and design process. However, these methodologies are not tailored to the unique characteristics of European space-based SoS. In particular, the above architectural methods do not satisfy the following extra needs that *ESA* has identified:

**Usage need.** In a European space programme, the decision making often involves a large variety and number of actors. These include technical actors (e.g. end-user and systems engineer), management actors (e.g. programme manager and procurement manager), and political actors (e.g. politician defining the strategic goals and program board evaluating the programme feasibility). The architecting meth-

odology must thus consider this variety and number of actors by enabling the actors to communicate at several abstraction/concreteness levels, using the most suitable means and tailoring the communication to European cultural differences. Addressing this need is key to maximise the effectiveness and alignment of technical and strategic decisions while ensuring the support of political institutions.

**Regulation need:** In a European space programme, several EU member nations are typically involved in the various programme phases, depending on the national interests and on the contribution to the European space programme. This multi-national involvement requires that national regulations (e.g. national design practices, data and security policies, governance procedures) are considered to effectively contribute to the successful programme development.

**Domain need:** The space domain presents different characteristics from other domains such as defence or IT. For example, space capabilities can be characterised by space-specific types and large set of parameters that are often unique within the entire domain. Similarly, the number of systems implementing a capability can be very limited if not unique. Furthermore, some interface control specifications might require a detailed level of representation to support the integration with legacy systems and promote the development of new and compliant ones. In addition, aspects like procurement policies also affect the space context in several ways. For example, ESA is subjected to geographical return criteria. In addition, ESA aims to harmonise technologies among European partners and to identify synergies at European level.

The above needs cannot be entirely addressed by existing architectural methodologies. For example, *DoDAF* and *MODAF* are tailored to the military domain and do not address issues such as data policies. In addition, these methodologies do not adequately support the representation of programmatic and procurement activities, which are central in the European space context. Similarly, *TOGAF* focuses on the modelling process. Moreover, by initiating a new methodology, *ESA* can also establish the infrastructure for the methodology modification and evolution, coordinating and receiving feedback from the European space industry for a long term standardization plan. These and similar considerations have motivated the introduction of the *ESA-AF* methodology described below.

#### 4. ESA Architectural Framework (ESA-AF)

*ESA-AF* introduces an architecting methodology for European space-based SoS engineering, aiming to address the above mentioned engineering needs. *ESA-AF* is based on the standard methodologies *TOGAF* and *MODAF*, tailoring and extending these methodologies to satisfy the above needs. We achieve this by deriving a set of technical requirements and by structuring *ESA-AF* in governance, modelling and exploitation levels.

## 4.1 Technical Requirements

The engineering needs have driven the identification of *ESA-AF* technical requirements. For example, from the *usage need*, we derived the technical requirements:

- *ESA-AF* shall improve the logical and technical consistency of existing architecting methodologies;
- *ESA-AF* shall reduce the complexity of existing architecting methodology, without affecting their effectiveness in European space-based SoS engineering activities;
- *ESA-AF* shall support its users in the exploitation of architectural data, by providing user-friendly visualisation of models.

Similarly, from the *regulation need*, we derived the requirements:

- *ESA-AF* shall introduce specific concepts for security policies, data policies, and financial regulations;
- *ESA-AF* shall enable the representation of European member nations.

Follows the *domain need*, from which we derived the requirements:

- *ESA-AF* shall enable the accurate representation of space domain concepts and their relationships;
- *ESA-AF* shall introduce a multi-resolution modelling approach where needed (e.g. in critical Signal-In-Space interfaces).

Finally, to support the possible long term standardisation, we have identified the requirements: *ESA-AF* shall be very adaptable to support the needs of ongoing and future European space programmes and to implement feedback from the European space industry; *ESA-AF* shall introduce software infrastructure to support the methodology evolution; *ESA-AF* shall provide accurate documentation for the use of the software infrastructure. All the technical requirements have been implemented by *ESA-AF*, which structure is illustrated below.

## 4.2 Framework Structure

The framework structure is organised in governance, modelling and exploitation levels, as shown in Fig. 1. Each level involves the participation a number of professional figures and supports a framework phase. Specifically, the governance level supports the maintenance, the modelling level supports the use, and the exploitation level supports the model data use.

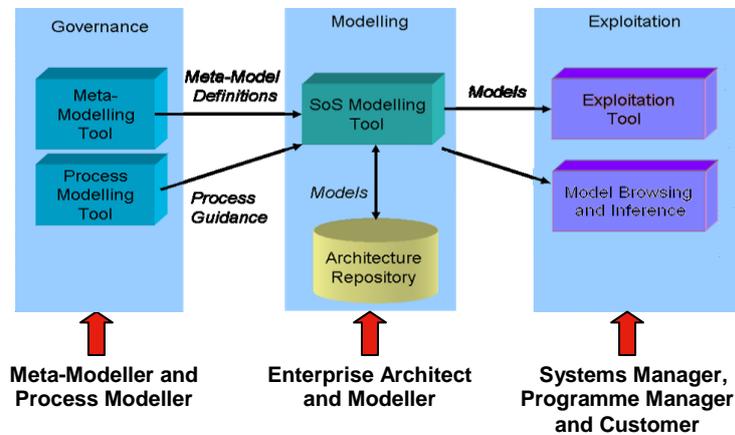


Fig. 1 ESA-AF Structure

#### 4.2.1 ESA-AF Governance

The *governance level* defines the software infrastructure and the business processes to support the methodology evolution, involving the meta-modeller and the process modeller.

The *software infrastructure* consists of data files representing *ESA-AF* definition data and the programs for the manipulation of these files. The data files are *ESA-AF* interactive glossary and *ESA-AF* meta-model implementation. The interactive glossary is a navigable set of web pages containing the definition of all the terms used in *ESA-AF*. *ESA-AF* meta-model implementation is the Eclipse-based implementation of *ESA-AF* meta-model, which is a reviewed and extended version of *MODAF* 1.2.003 meta-model (M3). Specifically, *ESA-AF* meta-model improves M3 logical consistency, simplifies M3 by removing unneeded concepts and views in the European space context, and introduces new concepts and viewpoints. *ESA-AF* meta-model consists of the following viewpoints: strategic, operational, systems, availability, technology, standards, programme, agreements, risk, financial, services, data policy and security. The viewpoints strategic, operational, systems, availability, technology, standards, programme are inherited from *MODAF*. These viewpoints were subjected only to minor reviews, such as the introduction of concepts and tagged values, to contribute to address the usage need. The remaining viewpoints have been specifically designed to address the regulation and domain needs. More specifically, the *Financial viewpoint*, which includes the *Cost and Funding views*, can be used to represent financial resources and the links of these resources to programmes, contributing nations, institutions and systems. The *Data Policy (DP) viewpoint* can be used to represent policies for any sort of information, including paper documents, scientific data, or project data. This viewpoint includes the *DP Definition*, *DP Validity*, *DP Provisioning* and *DP Use views* for the representation of the policy properties. The *Security viewpoint* can be used to

represent factors that can affect the security, including properties of information items and security regulations. This viewpoint includes the *Information Asset*, *Security Requirements* and *Security Solution* views for the representation of the respective security concerns. The programs are customised versions of the Eclipse Process Framework (EPF) and Eclipse Meta-modelling Framework (EMF) [10]. The *ESA-AF* EMF also includes a generator for the *ESA-AF* plug-in to be deployed within the software infrastructure of the modelling level.

The *business processes* define the procedures that meta-modeller and process modeller to update and modify the interactive glossary and the *ESA-AF* metamodel implementation. Currently, the processes are described in the *ESA-AF* documentation, which also refers to the Eclipse user guide and the documentation of the modelling software infrastructure.

Within this level, the *meta-modeller* maintains the modelling structure underlying any *ESA-AF* architectural model. Similarly, the *process modeller* maintains the business procedures describing and regulating the use of the methodology.

#### 4.2.2 *ESA-AF* Modelling

The *modelling level* defines the software infrastructure and the business processes that the modeller and the enterprise architect can use to represent European space-based SoS.

The *software infrastructure* defines the capabilities for the digital representation of European space-based SoS. These capabilities include the modelling tool Magic Draw (MD) [11], the *ESA-AF* plug-in, and the MD Teamwork Server. MD is a standard and popular tool for modelling, including UML. The *ESA-AF* MD Plug-in is the MD-based implementation of the *ESA-AF* meta-model. MD Teamwork server is a configuration management system for the reuse and sharing of individual model blocks across programmes and *ESA-AF* users. In addition, MD Teamwork also enables modellers and enterprise architect to concurrently and synchronously extend, review and visualise stored models. The business processes define the procedures for the improvement, analysis and evaluation of an *ESA-AF* enterprise model. These processes mostly conform to the *TOGAF* standard. However, improvements are introduced to guide the modeller in the SoS representation and to coordinate the modeller and enterprise architect for the identification of possible issues in European space-based SoS engineering, including design consistency and completeness [12].

Within this level, the *modeller* can represent European-based SoS architectures using *ESA-AF*. Similarly, the *enterprise architect* contributes to the architecture representation by supporting the modeller with domain knowledge.

### 4.2.3 ESA-AF Exploitation

The *ESA-AF* Exploitation defines the software infrastructure and the business processes that the modeller and the enterprise architect can use to extract information for decision making of the systems managers, programme managers and customers.

The *software infrastructure* consists of a configurable suite of tools for graphical and interactive visualisation and for tabular reporting generation. A visualisation tool provides enterprise architects and programme managers with a graphical and interactive overview of the SoS architecture, including relationships between service providers and service consumers, agreements regulating service use, systems involved in the operational and maintenance chains. The visualisation tool is configurable and can host new plug-ins offering improved functionalities, such as data flow interactive visualisation, data policy reporting or potential security risk detection. Similarly, a report generator tool can provide PDF documents of the main SoS properties, such as services involved in a scenario or owners of the systems implementing a set of services.

The *business processes* define a set model inference patterns that can guide the modeller to extract information from the architectural model by identifying specific systems properties [12]. Using these patterns, the modeller can identify the open interfaces (i.e. those system interfaces used across a stakeholder boundary) or support the mitigation of failure risks of the SoS or determine whether there are mismatch between agreement conditions and service levels, for example.

Within this level, the *modeller* can operate the visualisation tool, generate PDF reports and extract architectural information using the business processes. The *enterprise architect* can guide the graphical visualisation and enquire the modeller for more detailed data. The *system* and *programme managers* can visualise relevant parts of the SoS architecture and gain an insight into the development of the engineering activities while identifying strategic issues. Similarly, the *customer* can visualise the progress of the developments and the entire scope of the programme. An example part of the *ESA-AF* exploitation is illustrated in the following section.

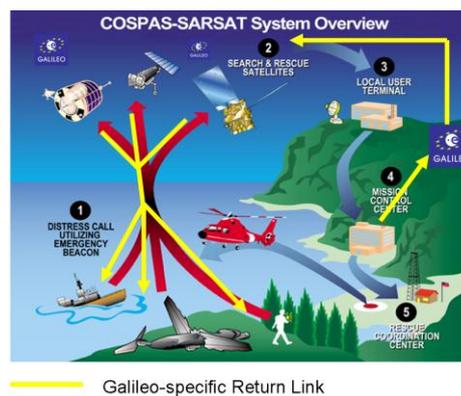
## 5. Example Applications

In our modelling support for space programmes, we have been applying *ESA-AF* to support SoS engineering for the *Galileo*, *GMES*, and *SSA* programmes.

## 5.1 Galileo

*Galileo* is the upcoming European Global Navigation Satellite System. *Galileo* is per se a complex system; however, *Galileo* will also form SoS configurations with systems of third-parties, enabling these parties to implement and provide advanced space-based services. Currently, the *Galileo*-COSPAS/SARSAT configuration is planned to be formed for the provision of global Search-and-Rescue (SAR) service [13]. In support to the engineering activities for this integration, we have developed a preliminary architectural model of this configuration, specifically for the *Galileo*-based SAR scenario shown in Fig. 2. The scenario is initiated by a human rescuee who activates a *Galileo*-enabled SAR device. Using *Galileo* direct link, the device transmits the distress signal to a local user terminal centre, which subsequently forwards the request to a local mission coordination centre. Using the *Galileo* reverse link, the mission centre acknowledges the reception of the distress signal to the human rescuee's device. Next, the mission centre plans the SAR mission, which is assigned to a rescue team. The team continues to rely on Galileo signal for the determination of the current position, while reaching the distress location.

Critical to the provisioning of the SAR service is the identification and definition of all the open interfaces (i.e. the interfaces between independently managed or owned systems) in the *Galileo*/COSPAS-SARSAT configuration [13]. The model purpose was to identify these interfaces, determining the responsibility for their definition and providing formal specification for the most critical interfaces [14]. The modelling began with the characterisation of the operational roles playing in the above scenario. Next, we have identified the systems that will play these roles, and basing on this we have determined the interaction occurring across organisation boundaries. For each of these interactions, the organisation responsible for the definition of the respective interface was identified, and the main critical interfaces formally defined through *ESA-AF*, including the one with the *Galileo* receiver [15].



**Fig. 2. Galileo-based Search and Rescue Operational Scenario.**



### 5.3 *Space Situational Awareness (SSA)*

The European *SSA* programme aims to establish a European system of warning about dangerous situations in the outer space [6]. In the programme preparatory phase, SoS functional and physical architectures are designed by evaluating possible integrations of existing assets located over Europe. Critical to ensure the reuse of the largest set of existing assets is that observation data are guaranteed to be disseminated and used only according to the data policy requirements of the individual European institutions owning or operating the assets. To gain the trust of these institutions and to ensure that their requirements are actually satisfied, we are applying the *ESA-AF* methodology to guide the functional architecture design and physical architecture verification activities for the *SSA* SoS. Currently, our model addresses the definition of an example data policy for Space Surveillance and Tracking (SST) data. This data policy specifies many attributes, including authorised data recipients and communication requirements. For example, authorised data recipients are only European military organisations and communication requirements include the use of physically secure connections. The model also includes the operational architecture, which involves *SSA* roles (e.g. *SSA* portal, *SSA* SST front-end, *SSA* SST back-end) and European partners (e.g. European MoDs, National Space Agencies, National Data Hubs and Data Collectors). In addition, the model defines the possible interactions among these roles and the information flow. Using *ESA-AF*, we have been able to specify values of the functional architectural parameters (e.g. protocol minimum encryption time, protocol repudiability time, or definition of interaction between two roles) basing on the example SST data policy. In the model, we have also outlined a prototypal representation of the *SSA* SoS physical architecture, including the mapping with operational roles on actual systems and capability configurations. Using *ESA-AF*, we will be able to ensure that the physical architecture meets the data policy requirements by verifying the congruence between the data policy specification and the properties of the systems storing or communicating the data [17,18].

## 6. Conclusion

In Systems of Systems (SoS) engineering activities, the *European Space Agency (ESA)* has identified needs concerning different types of use for architecting methodologies, representation of European regulations and policies, and representation of space-specific concepts. These needs cannot be completely addressed using existing architecting methodologies, and therefore a new methodology must be introduced to effectively support SoS engineering for ongoing and future European space programmes. In this paper, we have introduced the *European Space Agency Architectural Framework (ESA-AF)*, an architecting methodology that improves on existing methodologies by introducing methods and structure to address the identified needs. Specifically, *ESA-AF* aims to enable SoS engineering actors to communicate at several levels by defining information exploitation methods such

as inference patterns for architectural information extraction and software tools for user-friendly architectural visualisation. In addition, *ESA-AF* introduces new concepts, viewpoints and views for the representation of European and space-specific characteristics. *ESA-AF* also provides an infrastructure for the methodology evolution to support the implementation of feedback from European space industry and possible long term standardisation. We have shown three example applications of *ESA-AF* in support of SoS engineering activities for the *Galileo*, *GMES*, and *SSA* programmes.

## 6. References

1. Jamshidi, M., *Systems of Systems Engineering: Innovation for the 21<sup>st</sup> Century*, Wiley, 2009.
2. The Open Group, *TOGAF 9<sup>TM</sup> Enterprise Edition*, 2011.
3. MODAF Guidance, UK MoD, 2009
4. ESA, What is Galileo, [http://www.esa.int/esaNA/GGGMX650NDC\\_galileo\\_0.html](http://www.esa.int/esaNA/GGGMX650NDC_galileo_0.html)
5. GMES Project web page, <http://www.gmes.info>
6. Bobrinsky, N., and Del Monte, L., "The Space Situational Awareness Programme of the European Space Agency", *Cosmic Research*, 2010, Vol. 48, No. 5 pp. 392–398, Springer Verlag
7. ESA, Convention for the Establishment of a European Space Agency and ESA Council, ESA Publishing Division, SP-1271, October, 2003.
8. DoDAF V2.02 Volume 1 : Introduction, Overview, and Concepts - Manager's Guide
9. NAF, Nato Architectural Framework v.3, 2010.
10. Budinsky, F., Steinberg, D., Merks, E., Ellersick, R., Grose, T.J., *Eclipse Modeling Framework*, Addison Wesley, 2004.
11. Magic Draw, <http://www.nomagic.com>
12. Gianni, D., and Bowen-Lewis, J., "Inference Patterns for ESA-AF Models", ESA Technical Report, July, 2010.
13. Lisi, M., "Engineering a Service Oriented System: the Galileo Approach", *Proceedings of the 4th International Workshop on System & Concurrent Engineering for Space Applications (SECESA2010)*, Lausanne, Switzerland, October, 2010.
14. Gianni, D., Lewis-Bowen, J., Lindman, N., and Fuchs, J., "Modelling Methodologies in Support of Complex Systems of Systems Design and Integration: Example Applications", *Proceedings of the 4th International Workshop on System & Concurrent Engineering for Space Applications (SECESA2010)*, Lausanne, Switzerland, October, 2010.
15. Gianni, D., Fuchs, J., De Simone, P., Lindman, N., Lisi, M. "A Model-based Approach to Signal-In-Space Specifications for Designing Galileo Receivers", *InsideGNSS*, pp. 32 -39, Jan/Feb, 2011, vol. 6., n. 1.
16. Vega, SoSDEN Project Final Report, June, 2010.
17. Gianni, D., Lindman, N., Moulin, S., Fuchs, J., "SSA-DPM: A Model-based Methodology for the Definition and Verification of European Space Situational Awareness Data Policy", *Proceedings of the 1<sup>st</sup> European Space Surveillance Conference*, June, 2010.
18. Gianni, D., Lindman, N., Fuchs, J., Suzic, R., and Fischer, D., "A Model-based Approach to Support Systems of Systems Security Engineering for Data Policies", *INCOSE Insight*, special feature on Systems of Systems and Self-Organizing Security, pp. 18-22, July, 2011, vol. 14, n. 2.