A Case Study: Application of the Systems Engineering Modeling in the early phases of a Complex Space System Project

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Abstract

There is increased recognition of the role of systems engineering in reducing the risk (technical, cost, and schedule) on complex space systems development and integration projects. A number of international systems engineering standards have been published in the last five years (ISO 15288, IEEE 1220, and EIA 632). Closer to the space domain, NASA recently updated and finalized the NASA Systems Engineering Processes and Requirements guidelines (NPR 7123.1 and NPR 7120.5). Figure 1 represents an encapsulated perspective on the key systems engineering processes and their dependencies are articulated in the new NASA NPR 7123.1. The NASA acquisition framework (Figure 2) represents their recursive (across levels) and iterative (within a level) approach to the SE process, and includes milestones and reviews, as well as updates to those events. This paper will focus on the early phases of the systems engineering process. This represents the first two System Design Processes of Figure 1, and the Pre-Systems Acquisition Phase – the Pre-Phase A, Phase A and Phase B in Figure 2.

The paper will walk through a case study of a space system from the initial problem statement to defining the architectural technical risk to the program. The case study will show how early system engineering tools such as User Scenarios, Quality Function Deployment, and selection matrixes can be used in the initial system decisions to satisfy the NPR process. Then Systems Engineering Modeling will be illustrated in the context of a space systems case study [2]. Unique concepts such as active and passive stakeholders, and stakeholder capabilities and characteristics will be articulated to reduce the risk of misalignment between stakeholder expectations and technical system requirements. A framework for articulating a defined space mission into a set of well expressed and aligned technical requirements will be presented that satisfies the NPR process.

Key words – System Engineering Process, milestone, modeling, Space System, NPR

1 NASA Systems Engineering Processes and Requirements guidelines (NPR)

The goal of the NASA Systems Engineering Processes and Requirements guidelines (NPR) is to:

> *…establishes a core set of common Agency-level technical processes and requirements needed to define, develop, realize, and integrate the quality of the system products created and acquired by or for NASA. The processes described in this document (NPR 7123.1A) build upon and apply best practices and lessons learned from NASA, other governmental agencies, and industry to clearly delineate a successful model to complete comprehensive technical work, reduce program and technical risk, and improve mission success. The set of common processes in this NPR may be supplemented and tailored to achieve specific project requirements. [8]*

While this case study uses the NASA NPR, those readers familiar with the U.S. Department of Defense JCIDS (Joint Capabilities Integration Development System) or other formal systems engineering processes will recognize the systems development approach consisting of formal reviews and major milestones. Therefore, the applicability of this case study to other development projects should be applicable with adjustments to accommodate the specific approach to be used.

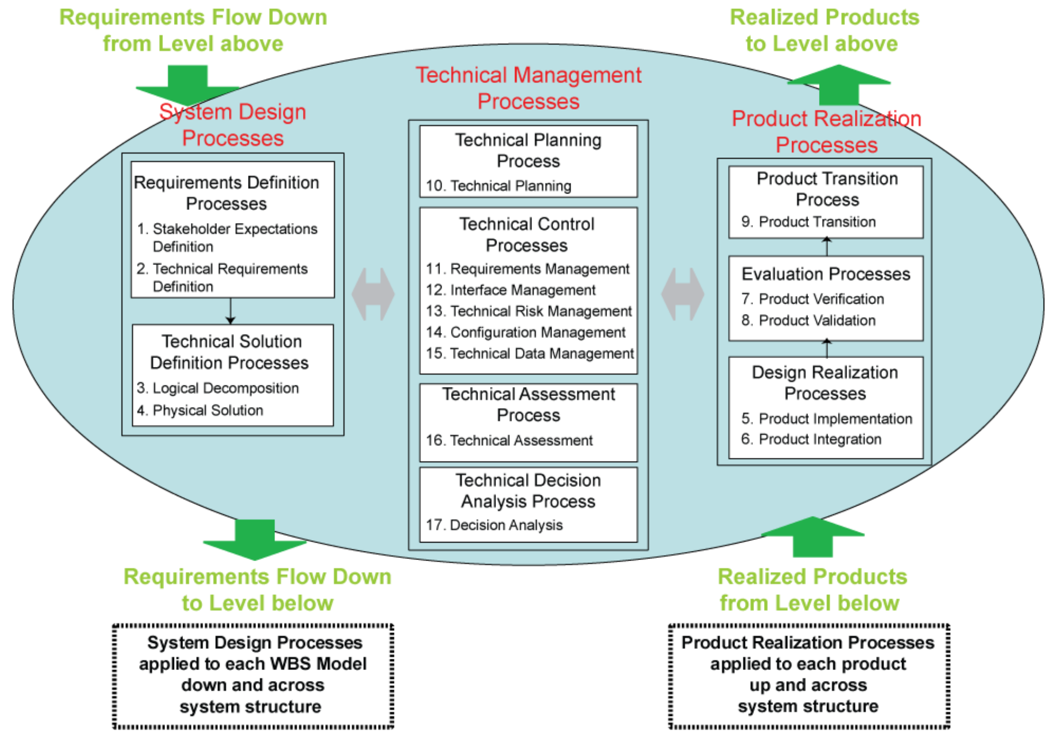

Figure 1 NASA Systems Engineering processes and their relationships [5]

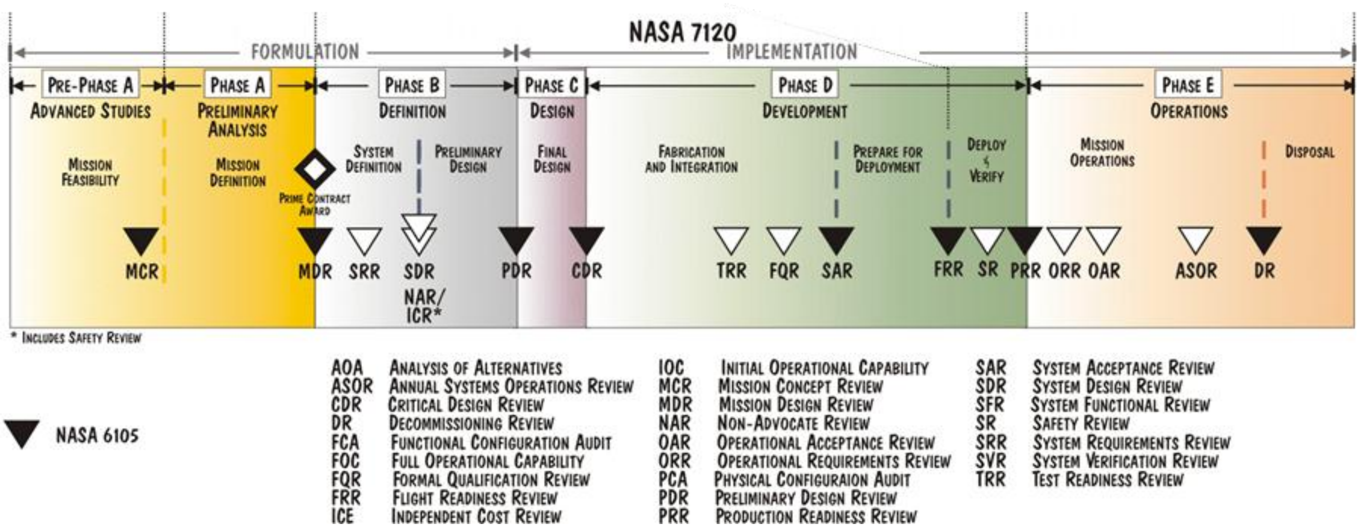

Figure 2 - The NASA Acquisition Framework [5]

1.1 Case Study Overview

Delft University of Technology in the Netherlands offers a Masters of Space Systems Engineering degree as part of their SpaceTech program aimed at mid-career professionals [2]. A major deliverable in that program is a team-based project. The Central Case Project (CCP) was designed to provide:

> *... a learning laboratory for participants to explore and use the competencies learned in the SPACETECH program - space-related markets, space systems engineering, inter-personal skills, business engineering and applications. It is a highly team oriented activity, allowing Participants to exercise their Business Engineering and Interpersonal Relations skills by working in a close-knit international team. [8]*

The data contained in this paper is an extraction of one such CCP. The course was proctored by Dinesh Verma of Steven's Institute of Technology (SIT) and the team was composed of international professionals from space industry and space agencies. The team had a year to complete the project. While the team did not follow the NPR process, this paper will show how the case study utilizes solid systems engineering techniques and satisfies the NPR requirements. Finally, even though the case study addresses both the systems engineering and business side of the project this paper will only address how the team performed the systems engineering activities and will not address the business engineering side of the program.

2 Advanced Studies (Pre-Phase A)

The first phase of the NPR process as seen in Figure 2 is the Advanced Studies (Pre-Phase A). This phase is defined in NPR 7120.5D as:

> *During Pre-Phase A, a pre-project team studies a broad range of mission concepts that contribute to program and Mission Directorate goals and objectives. These advanced studies, along with interactions with customers and other potential stakeholders, help the team to identify promising mission concepts(s) and draft project-level requirements. The team also identifies potential technology needs (based on the best mission concepts) and assesses the gaps between such needs and current and planned technology readiness levels. [4]*

2.1 Case Study: Statement Identification Process

Since the NPR process assumes the mission directorate is defined the team had to take a step back and develop the mission statement for the directorate. They did this by analyzing the mission need and came up with the following statement:

> *Overfishing and ocean pollution will lead to the potential extinction of native species with severe economical and ecological impacts. Environmental agencies need to prevent the depletion of marine resources by monitoring fishery activities and enforce the regulatory framework. Our ST7global communication system provides value-added surveillance services allowing worldwide vessel tracking.[1]*

2.2 Case Study: Stakeholder Expectations

Once the mission statement was created, the next systems engineering task for the team was: 1) the identification of all active and passive stakeholders, 2) definition of criteria selection for the "most critical" stakeholders, and 3) selecting the two most critical active and passive stakeholders in accordance with the criteria defined.

The identification process of the stakeholders started with the identification of the mission statement. In order to ensure the necessary traceability throughout the process, each stakeholder was assigned a unique identifier. This unique identifier is later used to facilitate for forward and backward requirements traceability.

2.2.1 Passive Stakeholders

Stevens Institute of Technology systems engineering course work defines the passive stakeholder as "individuals, entities, other systems, standards, protocols, procedures, regulations, which also influence the success of the system [6]". The team identified the passive stakeholders as: International Government Institutions (GOVIN), Maritime Regulations (MAREG), ITU Regulations and Frequency Allocation (ITU), Certification Standards (ISOST), External Terminal Interfaces (EXTIF), Communication Payload Interfaces to/from "Hosting" Satellite Platform (COMIF), and Ground Segment Interfaces (GRSEG) [1]. These stakeholders were categorized as passive because they drive the system requirements, imposing regulations and then requirements but are not considered direct end-user of the system data.

2.2.2 Active Stakeholders

Active Stakeholders are defined as "individuals, entities, other systems, which actively interact with the "system" when operational [6]". The team identified the active stakeholders as: National Fishing Agencies (NAFIA), National Maritime Environmental Agencies (or other equivalent national institution) (NMAEA), Coast Guards (COAGU), Fishing Company (FISCO), User of the Terminal (TERUS), Vessel (VESSE), System Service Operator (SSEOP), System Maintainer (SYSMA), Search and Rescue Organization (SAROG), and Maritime Fleet Management Operator (FLMGT) [1]. These stakeholders all will be direct end-users of the system once it is developed.

2.3 Case Study: Critical System Requirements Process

When the identification of stakeholders was established the team identified the potential customers. The team determined that the potential primary customers are the several Government Institutions (National Fishing Agencies, National Maritime Environmental Agencies Coast Guards) and the Vessel owners. In addition, once the system will be operational, services will be made available to the Fishing Companies, Search and Rescue Organizations.

The following selection criteria were defined to determine the most critical active and passive stakeholders were established:

> *Critical stakeholders are those who impose major driving constraints and requirements on the system/ product that shall be defined, designed and developed. The implementation of the underlying regulatory system is a MUST for the success of the system deployment. Other major requirement is the compliance with the interfaces to the existing external systems. [1]*

The application of the above criteria led to the identification of the following two most critical active and passive stakeholders, as listed below:

Table 1 - Active and Passive Stakeholders [1]

Active stakeholders	Passive stakeholders
Institutions - National Fishing Agencies, - National Maritime Environmental Agencies -or other equivalent national institution-, - Coast Guards	Maritime Regulations
User of the Terminal This selection is necessary to justify as there several candidates. Fishing companies also imposes major requirements on the service to be delivered. “User of the Terminal” was selected in accordance with the criteria “imposes major user requirements” on the terminal. The terminal being part of the system	Communication Payload Interfaces to/from “Hosting” Satellite Platform

2.3.1 Stakeholder Requirements

Once the stakeholders where identified and interviewed the team was able to develop stakeholder requirements for the system. These requirements were developed for each stakeholder and documented in a table. Publishing limitations prevent the authors from providing the set of requirements in this paper.

2.4 Mission Concepts

Once the stakeholder requirements were developed the team created five possible concepts that would satisfy the stakeholder requirements. These five concepts are listed in the table below.

Table 2Conceptual Alternatives [1]

Concept 1	Proprietary communication payload onboard Galileo satellites
Concept 2	Lease bandwidth on existing geostationary (GEO) communication satellites (i.e. – Inmarsat)
Concept 3	Lease bandwidth on existing geostationary (GEO) communication satellites, augmented through a constellation of micro-satellites in polar orbit
Concept 4	Proprietary communication payload on future geostationary (GEO) communication satellites, augmented through a constellation of micro-satellites in polar orbit
Concept 5	Proprietary constellation of dedicated communication micro-satellites in low earth orbit (LEO)

Once the five concepts were identified the team used a Pugh Matrix to compare the concepts against one another. From the Pugh Matrix and the team’s systematic analysis they chose Concept 3.

2.5 Advanced Studies (Pre-Phase A) Conclusion

The Case Study thus far as satisfied the NPR process by defining the mission directorate, identifying the stakeholders, defining the project level (stakeholder) requirements, and mission concept. Though the team did not identify the technology needs which is shortcoming of this case study when meeting the NPR requirements. Thus this is the end of the Pre-Phase A and the project is ready to move on to Phase A.

3 Concept & Technical Development (Phase A)

The next phase in the NPR process is the Concept & Technical Development (Phase A) which is defined by NPR 7120.5D as:

> *During Phase A, a project team is formed to fully develop a baseline mission concept and begin or assume responsibility for the development of needed technologies. This work, along with interactions with customers and other potential stakeholders, helps with the baselining of a mission concept and the program requirements on the project. These activities are focused toward System Requirements Review (SRR) and System Definition Review (SDR/PNAR) (or Mission Definition Review (MDR/PNAR)).[4]*

3.1 Case Study: Requirements Development

This phase was started by using use cases and a QFD to develop the functional and non-functional requirements of the system. The input into the use cases and QFD were the mission concept and stakeholder requirements developed in the pervious phase. The result was 26 functional and 17 non-functional requirements for a total of 43 requirements.

3.1.1 Case Study: User Scenarios

The first step of Phase A was to create user scenarios using a notation similar to UML sequence diagram. These scenarios are developed using the stakeholder requirements and the intent is to identify functional requirements for the system, from the Stakeholder perspectives. The scenarios were developed using information documented in the stakeholder requirements. Examples of the created scenarios are shown in Figure 3 and Figure 4.

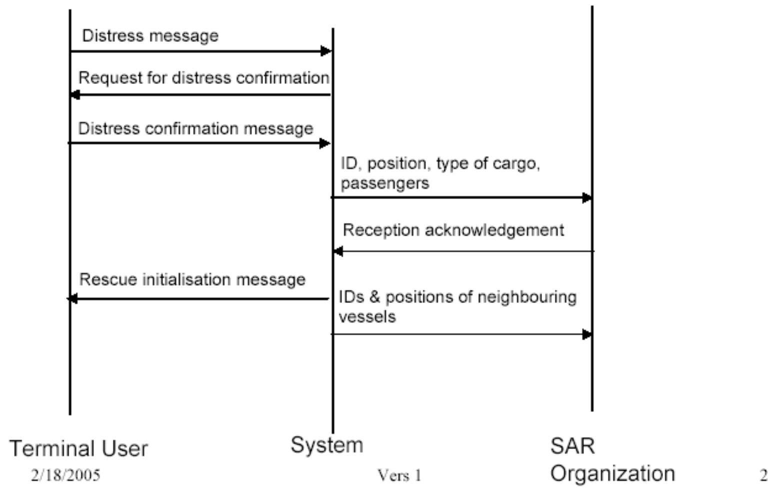

Figure 3 - User Scenario for GOVIN03 [1]

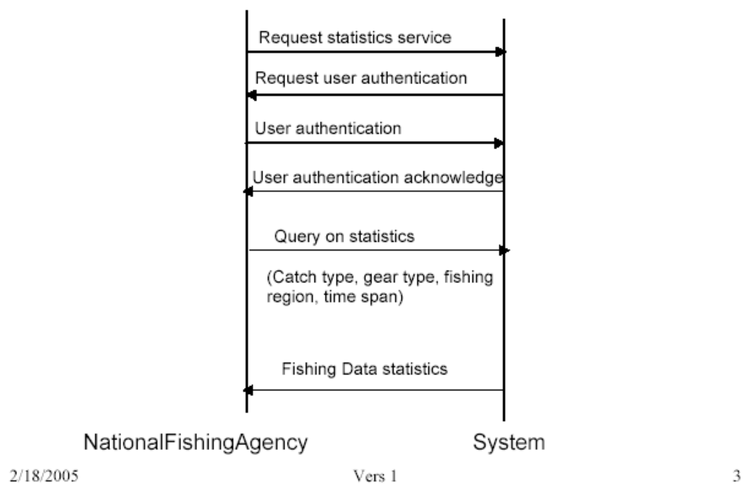

Figure 4 - User Scenario for NAFIA005 Stakeholder [1]

3.1.2 Case Study: Quality Function Deployment

The derived non-functional requirements were created using the Quality Function Deployment (QFD) methodology. By rating (high, medium/high, medium/low, and low) the stakeholder requirements against the design dependant parameters, the team can then use that rating to determine the appropriate non-functional requirement, as shown in Figure 5.

Characteristics			A	C	E	F	G	J	K	M	N	O	P	
Stakeholder requirements (Whats)	Design dependant parameters (Hows)	Requirement Importance (3 = highest, 1 = lowest)	Satellite footprint coverage	Number of satellites/payload	GNSS receiver & antenna	End-to-end System Availability	Communication bit error rate (BER)	Operational independ- ence (from terrestrial networks and other sats.)	Protection against external intruders	Terminal EIRP and G/T	Interoperability	Communication throughput	Number of users	Correlation: ● high, ⦿ med/high, ○ medium, ▣ med/low, □ low
Oceanic coverage MAREG008		3	●	▣										
Location accuracy FLMGT009		2			▣									
System availability of 24 h NAFIA004		3	⦿	●	▣	●		○			○	▣		
Message integrity COAGU012		2			●		⦿	▣		○				
System security COAGU013		2						⦿	●					
Near real-time data TERUS008		2								○	○	⦿	⦿	
Location refreshed 15 min FLMGT010		1	▣	▣			⦿			○		●		

Figure 5 - Quality Function Deployment [1]

4 Concept & Technical Development (Phase A) Conclusion

The input into this phase was the stakeholder requirements and mission concept developed in Pre-Phase A. These inputs were taken and from them the system requirements (functional and non-functional) requirements were developed using use cases and a QFD. At this point the system level requirements and mission concept are ready for review and to be baselined so the NPR process Phase A is complete.

5 Preliminary Design and Technology Conception (Phase B)

The next NPR phase is the Preliminary Design and Technology Conception (Phase B) which is defined as:

> *During Phase B, the project team completes its preliminary design and technology development. These activities are focused toward completing the Project Plan and Preliminary Design Review (PDR)/ Non-Advocate Review (NAR). [4]*

The NPR document 7120.05D also states that this phase requires the identification of risk drivers.

5.1 Case Study: Selection Matrix

A selection matrix was created to determine the five most critical system requirements. Each requirement was assessed in terms of its criticality. The criticality criteria were based on the following system aspects [1]:

1. System performance
2. System cost
3. System implementation risk
4. Conformity to law and regulations.

While the aspects 1, 2, and 4 do not require further explanation, the aspect 3 describes the risk of implementing the system. This comprises the criticality with respect to already existing space- or ground-based infrastructure as well as the schedule of the implementation of future space infrastructure, on which the system is relying.

The selection matrix comprises (43 x 4) elements (Figure 6), which were assessed independently by three team members. This process has been setup to avoid personal misperceptions from a single team member. The full selection matrix is given in Annex A5. The criticality has been judged by the number of 0 (no criticality), 1 (low criticality), 2 (moderate criticality), or 3 (high criticality) for each matrix element entry. The weight factors of the individual criticality aspects were all set to 1, i.e. indicating equal weights.

Criticality is judged by numbers 0 (no criticality), 1 (low criticality), 2 (moderate criticality), and 3 (high criticality) for each matrix element entry.

Type	Requirement #	Requirement statement	System performance	System cost	System implementation risk	Conformity to law & regulations	Sum
Functional requirements	SR001_GOVIN003	The system shall be able to receive "distress message" from the system user's.	1.3	1.0	1.0	1.0	4.3
	SR002_GOVIN003	The system shall acknowledge the "distress message"	1.0	2.0	1.3	0.3	4.7
	SR003_GOVIN003	The "distress message shall include the following data:	1.7	1.0	0.7	0.7	4.0
	SR004_GOVIN003	The system shall request for distress confirmation to the system user's	1.7	1.7	1.3	0.3	5.0
	SR005_GOVIN003	The system shall receive a distress confirmation message from the distressed system users.	1.3	1.3	1.0	0.7	4.3
	SR006_GOVIN003	The system shall inform the SAR Organization about the distress.	1.3	0.7	0.7	1.0	3.7
	SR007_GOVIN003	The system shall send a "rescue initialisation" message to the distressed terminal user.	1.7	1.3	1.0	1.0	5.0
	SR008_GOVIN003	The system shall be able to identify tot and localize vessels in the neighbour area of the distressed one	2.0	2.0	1.3	1.7	7.0
	SR009_GOVIN003	The system shall communicate to the SAR Organizations the localization and identification of the other vessels.	1.7	1.3	1.3	1.7	6.0
	SR010_NAFIA006	The system shall be able to check user authentication, ie that user is allowed to access statistic fishing data.	2.0	1.3	1.7	2.0	7.0
	SR011_NAFIA006	The system shall provide statistic fishing data only to users which have permission to access statistics data.	2.0	1.3	1.7	2.0	7.0
	SR012_NAFIA006	The system shall reply statistic fishing data on query for catch type, gear type, time span, region	2.3	1.7	2.3	1.7	8.0
	SR013_NAFIA006	The system shall reply statistic fishing within TBD hours.	1.0	1.0	1.0	0.7	3.7
	SR014_NAFIA006	The system shall hold statistic fishing data for a period of 5 years.	0.7	1.3	1.0	1.0	4.0
	SR015_NAFIA006	The system shall be able to check user authentication, ie that user is allowed to access Vessel information data	2.0	1.3	1.7	2.0	7.0
	SR016_NMAE004	The system shall provide Vessel information data only to users which have permission to access Vessel information.	2.0	1.3	1.7	2.0	7.0
	SR017_NMAE004	The system shall reply Vessel information data on query for Vessel ID.	2.0	1.7	1.3	0.7	5.7
	SR018_NMAE004	The vessel information data on query for Vessel ID shall compile: Vessel ID, position, course, speed, cargo info.	2.0	2.0	1.7	1.0	6.7
	SR019_NMAE004	The system shall regularly receive Vessel information transmitted from the Vessel.	2.0	2.0	1.7	0.3	6.0
	SR020_EXTIF007	The system's terminal shall provide the current time, position and velocity of the vessel at a rate of 0.5 Hz.	1.0	1.3	1.0	0.0	3.3
	SR021_EXTIF007	The system's terminal shall accept requests for current time, position and velocity of the vessel from the terminal user.	1.3	0.3	0.3	0.3	2.3
	SR022_EXTIF007	The system's terminal shall be able compute the current time, position and velocity of the vessel at a rate of 0.5 Hz.	1.0	0.7	1.3	0.0	3.0
	SR023_NMAE002	The system shall provide Vessel information data only to users which have permission to access Vessel information.	2.0	1.3	1.7	2.0	7.0
	SR024_NMAE002	The system shall reply Vessel information data on query for Vessel ID.	1.7	1.3	1.0	0.7	4.7
	SR025_NMAE002	The vessel information data on query for Vessel ID shall compile: Vessel ID, position, course, speed, cargo info.	1.7	1.7	1.3	1.0	5.7
	SR026_NMAE002	The system shall regularly receive Vessel information transmitted from the Vessel.	2.0	1.7	1.3	0.3	5.3
Non-functional requirements	SNFR001_MAREG008_AC	The field of view of the communication payload onboard a geostationary satellite shall be 100 degree minimum. This figure is based on a GEO constellation of 4 satellites, equally spread along the equator.	2.0	2.0	1.3	1.0	6.3
	SNFR002_FLMGT009_E	The terminal shall suppress multipath.	2.0	1.3	1.7	0.0	5.0
	SNFR003_FLMGT009_E	The terminal shall allow ionospheric correction.	2.0	1.7	1.0	0.0	4.7
	SNFR004_FLMGT009_E	The terminal shall allow dual-frequency GNSS reception.	2.0	1.7	1.7	0.3	5.7
	SNFR005_NAFIA004_F	The communications payload on a GEO shall be available and operational 99.99% (TBC).	2.3	2.3	2.3	0.3	7.3
	SNFR006_NAFIA004_F	The ground system availability shall be higher than 99.99% (TBC).	2.3	2.3	2.0	0.3	7.0
	SNFR008_COAGU013_K	The system data (identified as sensitive) being communicated shall be encrypted proposed to be changed to The system shall encrypt all data received from government vessel and transmitted to government agencies.	2.0	1.7	1.7	1.7	7.0
	SNFR009_COAGU013_J	The radio frequency (RF) signals used by the system shall be resistant to jamming and anti-spoofing.	2.0	1.7	2.7	2.0	8.3
	SNFR011_COAGU013_K	The system shall authorize all users through unique identification numbers.	1.0	1.0	1.0	0.7	3.7
	SNFR012_NAFIA004_J	Using the system's gateway station, the system shall have the capability to bypass terrestrial communication networks, in the event of lost terrestrial connectivity. The system shall operate safety-of-life channels with 100 capacity during all host satellite maintenance, stationkeeping or outage activity. The system shall operate standard communication channels at 50 % (TBC) capacity during host satellite maintenance, stationkeeping or outage activity.	2.3	2.3	2.0	1.0	7.7
	SNFR013_TERUS008_P	The system shall have a capacity of 200 000 terminal users (TBC) when launched with a capability to grow to 500 000 terminal users (TBC).	3.0	2.0	2.0	1.0	8.0
	SNFR014_TERUS008_M	The system's terminal shall have a minimum gain to temperature ratio of (TBC) dB/K.	2.0	1.7	1.7	0.0	5.3
	SNFR015_COAGU012_G	The system shall guarantee a bit error rate (BER) as follows if the link margin is greater than 0 dB, a. 10-5 (TBC) for daily message traffic, b. 10-7 (TBC) for safety-of-life message traffic.	1.7	1.7	1.7	0.0	5.0
	SNFR016_FLMGT010_C	The system shall have a constellation of satellites/payloads such that a single terminal is in view of a single satellite/payload for no less than 15 (TBC) minutes.	2.0	2.0	1.7	0.0	5.7
	SNFR017_TERUS008_M	The forward link of the system's terminal shall provide a minimum Effective Isotropic Radiated Power (EIRP) of (TBC) dBW. This minimum EIRP includes terminal transmitter RF signal power, transmit circuit losses, and transmit antenna gain.	1.7	1.7	1.3	0.0	4.7
	SNFR018_TERUS008_O	The message latency in the system shall be less than 60 seconds (TBC).	1.7	1.3	1.3	0.0	4.3
	SNFR019_FLMGT010_O	Each active terminals location shall be transmitted to the communication payload every 15th minute.	2.3	1.3	1.7	0.0	5.3

Figure 6 - Selection Matrix [1]

5.2 Case Study: Architecture Technical Risk to Project

The next step was to define the critical architectural technical risks to the project. To do this a Functional View (Figure 7) and Physical View (Figure 8) of the system was developed using the Mission concept and requirements defined in the previous phases. One important output of developing the views was that the team agreed and identified the following major architectural technical risks [1]:

- ST7 System dependency from the 2 major external interfaces
    - Inmarsat
    - GNSS

  The selected system concept is based on the utilization of Inmarsat and on GNSS systems. This constitutes an external dependency of the ST-7 system architecture and therefore architectural guidelines have to established as well as requirements like that the system shall also be capable to utilize the ORBCOMM system in case of Inmarsat unavailability.

  The dependency to GNSS is to be highlighted. It has also to be highlighted that the ST-7 system should be able to work with GPS/Glonass/Galileo.

- ST7 User Terminal
  The technological development of the User Terminal seems currently a challenge. The terminal shall be developed to communicate to two space systems (Inmarsat and the ST-7 microsatellite)

- External Interface Risk
  The User Terminal shall be configured in such a way that they can simply replace the systems already in use (i.e. the Automatic Identification System). This interface is currently not yet baselined and this compatibility issue shall be assessed and resolved in the early stage of the project.

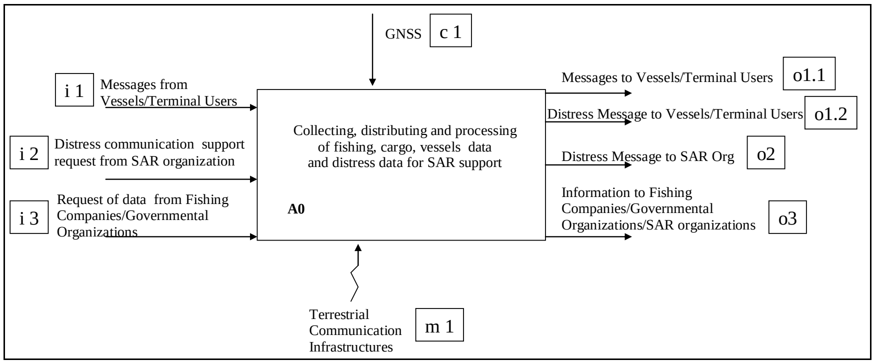

Figure 7 - Functional Architecture View [1]

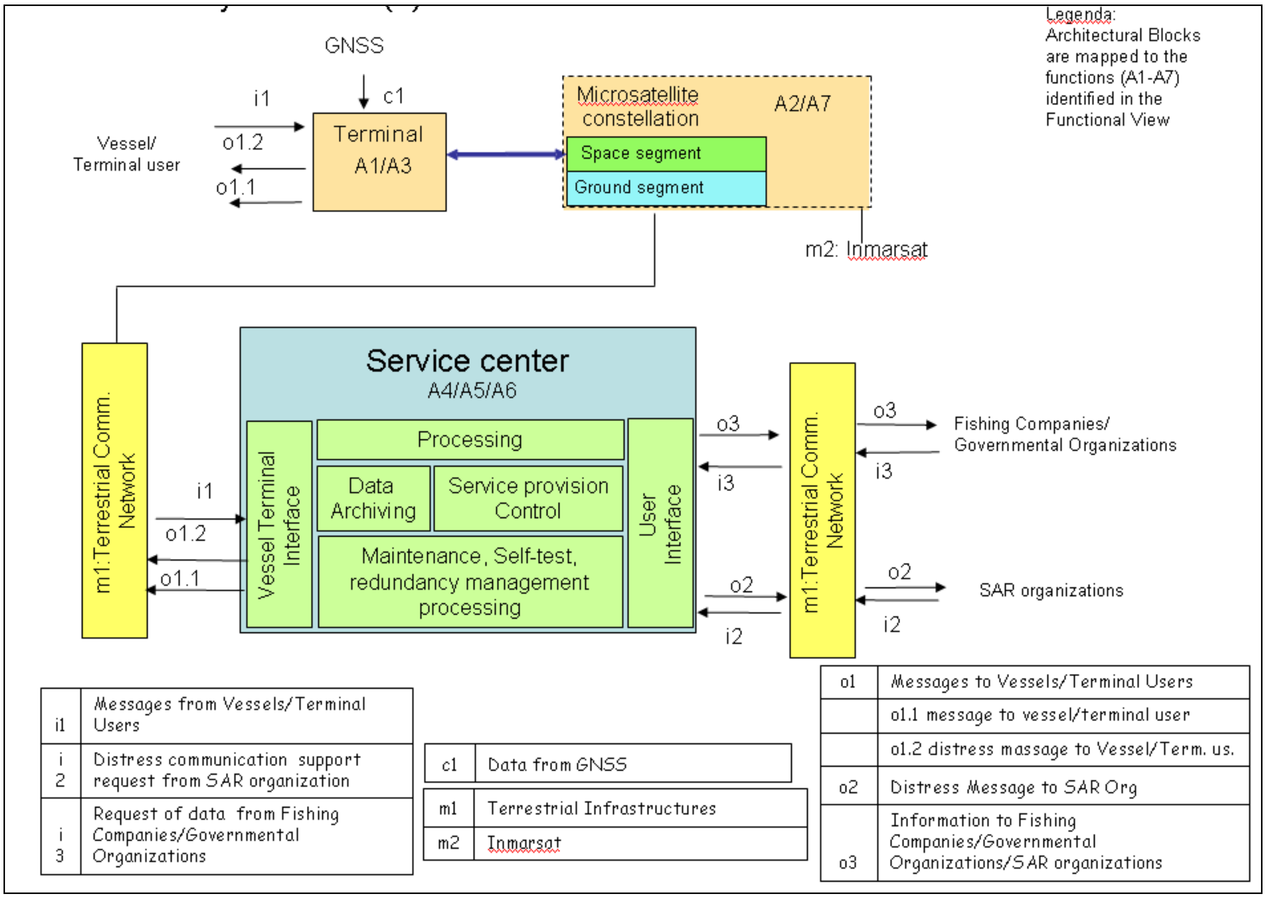

Figure 8 - Physical Architecture View [1]

5.3 Case Study: Risk Reduction

In order to cope with the above major architectural technical risks, the following four architectural guidelines were identified by the team [1]**:**

- <u>Scalability/ Growth Capability</u>
  The proposed architecture shall be scalable and allow to easily accommodate new functionalities and/or additional features to reply to new stakeholders needs (e.g. extend the number of monitored vessels, add new functionalities such as vessel collision avoidance). As and example the implementation of such an architecture guideline will led to the "separation" of ground center functionalities, in order to facilitate the functional upgrading process.

- <u>Modularity</u>
  A Modularity architectural guideline shall be implemented both for the Ground Segment design and the User Terminal. In particular for the User Terminal, this guideline will be translated into an interface/functions decoupling. This will allow designing the user terminal in such a way to separate the processing functionalities from the interface functionalities (i.e. in such a way a replaceable unit will be used to interface to Inmarsat or to Orbcomm –in order not to be fully dependent on Inmarsat).

- Fault Tolerance
  Considering the system availability requirements, the system architecture shall be tolerant to failures, in order to provide a "24 hours" service. This architectural guideline will be then implemented thru physical redundancy of the architectural elements and/or processing/ communication chain (both on space and on ground).

- Security
  The system architecture shall be implemented in line with a stringent security guideline. As an example this will led to the implementation of message encryption, reliable access to system resource and firewalls).

5.4 Preliminary Design and Technology Conception (Phase B) Conclusion

The case study defined the system architecture from both the functional view and physical view so the PDR that is required by the NPR process can be performed. The risks are also identified, using systems modeling techniques, as requested by the NPR process. Although the team did not address the technology development required by the NPR so that is one aspect that is not met by this case study.

6 Conclusion

This paper has presented a case study that was conducted to represent the front-end systems and business engineering of a space-based maritime communication and navigation system. Overall the case study satisfies the NPR process Pre-Phase A, Phase A, and Phase B. The case study used solid systems engineering techniques and even though was not originally performed using the NPR process it satisfies all the requirements except for those pertaining to the technology development. The use of systems modeling in Phase B allowed the team to define the risk associated with the architecture and the team was able to define risk reduction techniques. The modeling used in this case study shows how early employment of system modeling can be useful in allowing a team to identify and mitigate architecture risk early in a program.

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