A Requirement Evaluation Metric Applied on the ITASAT-1: A Small Technological Satellite

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Available data demonstrates that defective requirements are a dominant cause of cost and schedule problem on aerospace programs. This work presents results obtained from a particularly study of a Requirement Evaluation Metric applied on a small technological satellite called ITASAT-1. The requirement evaluation metric is a structured methodology for measuring the quality of requirements, individually and collectively by means of 10 (ten) individual quality metrics. The paper describes the satellite mission, the Requirement Evaluation Metric used, and how it was applied. In addition, the requirement engineering process is shown in terms of the problem statement. The main contribution of this study is the establishment of a Requirement Evaluation Metric on a systematic approach to refine a critical satellite requirements operation for space applications, called COFI-ref.

I. Introduction

It is known that the software development process is conceptually an abstract form of model transformation. It starts from a stakeholder model requirements analysis and go through the system design model [9, 10]. The success or failure of such transformation depends mainly of the initial model that captures the user needs. The same process occurs to acquire the user concerns for a space mission operation. Advanced satellite systems require new approaches not only in the area of the satellite itself but also in the field of operations [2, 3, 4].

This paper presents a Requirement Evaluation Metric applied on the early phases of the ITASAT-1 satellite requirements as part of the Verification and Validation (V&V) plan. The evaluation metric used, called Requirements Structural Model, was presented for the first time by Robert J. Halligan[9]. The ITASAT Program was established by the Brazilian Space Agency (Agência Espacial Brasileira – AEB) and developed in cooperation with the National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais – INPE), the Technological Institute of Aeronautics (Instituto Tecnológico de Aeronáutica – ITA) and other universities, including the *Technische Universität Berlin*, in Germany. The goals of the Program are: (a) the generation of technological innovations for the aerospace sector; (b) the strengthening of the national industry; (c) the dissemination of knowledge; and (d) the training of human resources. This task is performed through conceptualization, design and development of small satellites and applied research related to the national interests.

The COFI-ref (Conformance and Fault Injection for Requirement Refinement) approach is based on a testing methodology called COFI (Conformance and Fault Injection). As part of the ISVV (Independent Software Verification and Validation) process, the results with the application of the COFI methodology has surprised the mission management as many errors were found [1, 2]. However, the errors were found only in latter phases. Thus a variation of COFI, the COFI-ref was developed to be applied in early phases of the ITASAT Mission, as part of the mission requirement refinement. With this opportunity it was possible to demonstrate the effectiveness of focus the designer’s attention to incomplete, ambiguous and incorrect requirements that occur during the software development process and operations definition. Finally, the Requirement Evaluation Metric was applied during the COFI-ref in order to measure the requirement refinement provided by this approach.

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This paper is organized as follows:

a) Section 2, describes the ITASAT-1 concept and the COFI-ref approach;
b) Section 3, presents the Requirement Evaluation Metric;
c) Section 4, describes the Application of Requirement Quality Metrics and the results obtained;
d) Section 5, presents a conclusion and lessons learned.

II. Problem Statement

This section describes the ITASAT-1 mission with the satellite operation modes, and the COFI-ref approach.

A. ITASAT-1 Concept

The ITASAT-1 System Engineering Team is responsible to produce the related documents at system-level and though a formal review delivery the respective document to the V&V Team as starting point of Refinement process as part of the COFI-ref approach showed on Fig. 3. The Document Requirements Definition (DRD) is the input for the refinement process. This section will describe part of the DRD that contextualize the problem domain.

The mission cycle comprehends the following phases:

a) Assembly, Integration and Test Phase (AITP);
b) Launch Readiness Phase (LRP);
c) Pre-launch Phase (PLP);
d) Launch and Early orbit Phase (LEOP)
e) Commissioning Phase (CP);
f) Operational Phase (OP); and
g) Decommissioning Phase.

As part of the Mission Description Document the ITASAT-1 has 8 operational modes:

a) Launch Mode;
b) Survival Mode;
c) Testing Mode;
d) Alignment Mode;
e) Payload Mode;
f) Experimental Mode;
g) Operational Mode; and
h) Propulsion Mode.

Figure 2 shows the operational modes and the relationship between them. It is important to realize that this figure is drawn exactly as it is in the DRD

Figure 1. ITASAT System related to data collection, where the ITASAT-1 satellite plays a very important role to the continuity of the Brazilian Environmental Data Collection System.

As shown on Fig. 2 we can realize that the Operation Modes merges between them. The Launch and Survival Modes belongs to the Launch and Early Orbit Phase as well as Testing Mode that belongs to the Commissioning Phase. However the Testing Mode, Survival Mode and Propulsion Mode belong to the Decommissioning Phase. Finally the Alignment, Operational, Experimental and Payload Modes belong to the Operational Phase.

A description of the operational modes is given below.

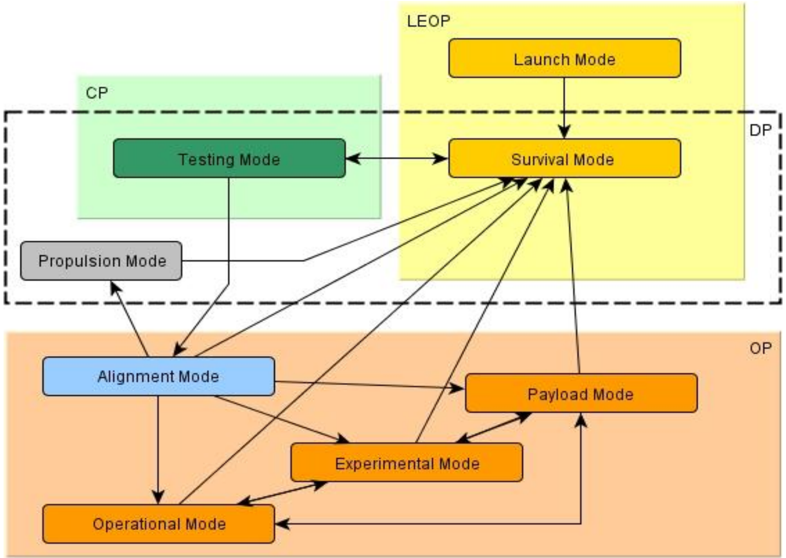

Figure 2. Operation Modes of the ITASAT-1 spacecraft.

Launch Mode - During the launch the s/c (spacecraft) stays in the launch mode. It fulfills the launch provider requirements. There is no electric power supply for all subsystems and all mechanisms are securely locked.

Survival mode - After ejection the s/c changes into the survival mode. In this mode, the attitude of the s/c and its spin rate is undefined. In this mode all payloads (operational and experimental) are turned off. The same is ACS. In this mode the task of the s/c is to keep a positive energy budget over one orbit and to ensure it ability to communicate well. In the case of failure or malfunction that affects the whole s/c it switches into the survival mode automatically, independent of the current mode.

Testing mode - From the survival mode the s/c switches into the testing mode. This mode is a possibility to test all the subsystems and payloads before passing the s/c to the costumer. The testing mode provides all the functions of the survival mode and in this mode the first telecommand data will be received. After this mode the s/c can change to the alignment mode or the payload mode. Starting from this mode it also can be decommissioned.

Alignment mode - The alignment mode is for de-tumbling the s/c and to align it to specified orientations in the flight coordinate system. It is an intermediate mode from the Testing mode to the Payload mode, the Experimental mode, the Operational mode or the Propulsion mode.

Operational mode - In this mode the experimental payload is turned off and just the operational payload is working, besides the subsystems.

Propulsion mode - The Propulsion Subsystem is used for de-orbiting and therefore belongs to the Disposal Phase.

Payload mode - In this mode, achieved from Alignment mode by ground command, all satellite subsystems including the payload, but excluding the possible propulsion system, is in their final operating configuration. The mission technological data is being collected and transmitted to Earth during visible passes.

Experimental mode - In this mode besides the subsystems just the experimental payloads are working. This mode provides time to do experiments and to test for example the new onboard computer

Next section will present a description of the COFI-ref approach.

B. COFI-ref Approach

The COFI testing methodology[1, 2, 13] consists of a systematic way to create test cases for reactive systems. The system to be tested is modeled in Mealy machines. In COFI the system behavior is partially represented in state models where transitions represent inputs and outputs of the interfaces. Figure 3 shows the main steps of the COFI-ref approach and its intersection with COFI Methodology. The steps for COF-ref are:

a) DRD Acquisition
b) Identification;
c) State-Based Modeling; and
d) Requirement Refinement.

For COFI Methodology the steps are 2: Identification, 3: State-Based Modeling, and 4: Automatic Test Case Generation where steps 2 and 3 were reused on COFI-ref.

The DRD (Document Requirements Definition) is the input of the COFI-ref. In the first step, the team in charge of the system specification, before a project review, provides the DRD for the COFI-ref team. This is what we call "DRD Acquisition". The second and third steps were extracted from the standard COFI methodology. The tasks involved in second step, the Identification, are:

a) Identify the services that a user recognizes;
b) Identify hardware faults that can occurs (and that system shall resist);
c) Identify the events (inputs) and reactions (outputs) of the system.

For step 3 we have to create partial models based on Finite State Machines. The tasks involved are to define, for each Service previously created:

a) Normal Operation Mode;
b) Specified Exception;
c) Sneak Paths; and
d) Fault Tolerant.

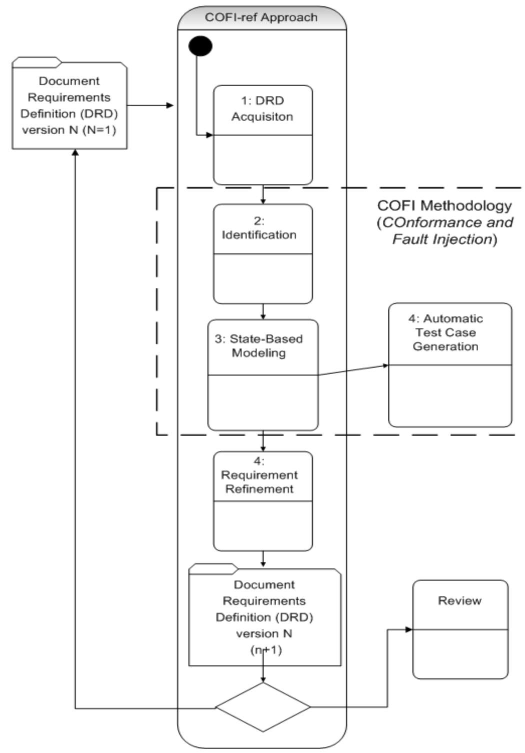

Figure 3. COFI-ref main steps.

For the last step, the Requirement Refinement represents the refinement itself requiring the execution four tasks:

a) State Models analysis, based on its transitions;
b) Question elaboration; and
c) Requirements modification.

For details of the COFI-ref approach and results, see previous works [12, 13].

III. Requirement Evaluation Metric

Requirements quality, in order to satisfy the user needs and system performance should follow the same criteria no matter the area or description being writing about. That is, the requirements must, in their expression, exhibit certain attributes as quality factors [9, 10]. Those quality factors can be classified as follows:

a) Correctness: refers to an absence of errors in the statement of requirement;
b) Completeness: refers that the requirement contains all of the information that satisfy constraints and conditions to enable its implementation and verifying process;
c) Consistency: requires that requirement not be in conflict with any other, nor element of its own structure;
d) Clarity: requires that the requirement be readily and understandable without semantic analysis;
e) Non-ambiguity: requires that there are only one semantic interpretation of the requirement;
f) Connectivity: refers to the property whereby all of the terms within other requirements are adequately linked in terms of words and definitions;
g) Singularity: refers to the property that the requirement cannot sensibly be expressed as two or more requirements having different meanings, like verbs or objects;
h) Testability: refers to the existence of a finite and object process with which to verify that the requirement has been satisfied;
i) Modifiability: requires that any change in requirement can be made completely and consistently in order to obey the previous criteria; and
j) Feasibility: requires that a requirement be able to be satisfied within natural physical phenomena and applies to the project.

The Requirement Evaluation Metric is based on those criteria, once it is possible to establish a measurement to characterize the quality, and quantify the requirements. The metric are called Requirement Structural Model and it was developed by Robert J. Halligan [9]. Once requirements are most commonly expressed as natural language statements, although graphical and formal mathematical requirements languages are widely used in many types of system modeling. The author says for natural language type of expression, requirements quality metrics may be developed through the parsing of each requirement statement into the elements of a structural model of a sound requirement, a template. Table 1 shows an example of ITASAT-1 system requirement parsed into the template. This procedure was used in all system requirements evaluated by the COFI-ref approach [12].

Original Requirement:

Alignment mode - The alignment mode is for de-tumbling the spacecraft and to align it to specified orientations in the flight coordinate system. It is an intermediate mode from the Testing mode to the Payload mode, the Experimental mode, the Operational mode or the Propulsion mode.

Table 1. Requirement Structural Template.

Element	Text
Actor	The alignment mode
Conditions for Action	de-tumbling the spacecraft; flight coordinate system
Action	is
Constraints of Action	
Object of Action	spacecraft
Refinement/Source of Object	align it to specified orientations; an intermediate mode
Refinement/Destination of Action	
Other	from the Testing mode to the Payload mode, Experimental mode, the Operational mode or the Propulsion mode.

The author says that a strong requirement shall have each applicable element of the requirement (presented in Table 1), and the requirement overall, satisfying each of the quality factors described earlier. This ideal provides a basis of the development of requirements quality metrics. Figure 4 illustrates the construction of a set of a metrics based on parsing of a requirement into the template. The basis for the development of requirement quality metrics are defined below:

IRQ – Individual Requirement Quality

This metric is applicable for a single requirement and have to be numbered between 0 and 1, where 1 represents a 'perfect' requirement and 0 (zero) a totally defective one. The metric is developed through a classification and the parsed version of the requirement, following the steps bellow:

a) To determine which of the possible seven elements of the structure are applicable and assigning value of 1 to each applicable element;
b) To assess each element of the parsed requirement against the quality factor criteria, and scoring each applicable element as 1 (satisfactory) or 0 (unsatisfactory). An element may be unsatisfactory because it is missing, or because it is defective in some other way;
c) To calculate the metric by dividing the sum of the applicable element values into the sum of the element scores.

IQF1 – IQF10 – Individual Quality Metrics

Ten individual quality factors correspond to the ten requirement quality factors as follows:

IQF1 – Correctness;
IQF2 – Completeness;
IQF3 – Consistency;
IQF4 – Clarity;
IQF5 – Non-Ambiguity;

IQF6 – Connectivity;
IQF7 – Singularity;
IQF8 – Testability;
IQF9 – Modifiability;
IQF10 – Feasibility.

These metrics assume, for an individual requirement a value on the unit interval [0,1] depending on whether the requirement overall has a defect of type 0 (zero) or not (1). The application of this metric follow the steps bellow:

a) To classify the requirement statement according the eight elements presented on Table 1earlier;
b) To assign, for each of the element identified on step before, 1 if the statement presents the element or 0 (zero) if not;
c) To analyze each of element identified against the ten quality factors and score the requirement to 1 if its correct and 0 (zero) if not;
d) To evaluate each element identified on step (a) against the ten quality factors and score to 1 if it is satisfactory or 0 (zero) if not;
e) To calculate the Individual Requirement Quality for each requirement dividing the sum of the elements with the sum of the score.

Requirements which have been omitted may be accounted for by estimating an omission ratio for each requirement that is present. The omission ratio is the number of new requirements that would be created if all possible areas of omission suggested by the requirement that is present were pursued to resolution. The omission ratio must be constructed such as to support aggregation of requirements having different omission ratios.

The quality metrics for a sets of requirements correspond to, and are produced from, the individual metrics, as follows (for n requirements):

RQ – Requirements Quality

$$RQ = \frac{\sum IRQ}{n} \quad (1)$$

QF1 - Correctness

$$QF1 = \frac{\sum_{i=1}^{n} QF1}{n} \quad (2)$$

QF2 - Completeness

$$QF2 = \frac{\sum_{i=1}^{n} QF1}{n} - \frac{\sum_{i=1}^{n} omission\_ratio}{n} \quad (3)$$

Where,

a) n is the total of requirements evaluated;
b) QF2 can be negative, once take into account the omission ratio;
c) QF3 to QF10 are derived as for QF1.

Table 2 illustrates the construction of the Requirement Structural Model based on parsing of the original requirement statement presented earlier.

Table 2. Construction of Requirement Quality Metrics.

Element	Text	Applicability	Score	Metric Name	Metric Value
Actor	The alignment mode	1	1	IQF1	0
Conditions for Action	de-tumbling the spacecraft; flight coordinate system	1	0	IQF2	1
Action	is	1	1	IQF3	0
Constraints of Action		1		IQF4	0
Object of Action	spacecraft	0	0	IQF5	1
Refinement/Source of Object	align it to specified orientations; an intermediate mode	1	1	IQF6	1
Refinement/Destination of Action		0	0	IQF7	0
Other	from the Testing mode to the Payload mode, Experimental mode, the Operational mode or the Propulsion mode.	-	-	IQF8	1
	SUM	**5**	**3**	IQF9	0
	Metric IRQ	0,60		IQF10	1
	Omission Ratio	1		**SUM**	**5**

Next section presents the results obtained applying the Requirement Structural Model on ITASAT-1 system requirements.

IV. Application of Requirement Quality Metrics

The Requirement Structural Model was applied on system requirements during the earlier phases of ITASAT-1 Mission right after and before the COFI-ref approach. This procedure was used in a way to measure the quality of the COFI-ref refinement approach.

This section shows the results that were achieved applying the Requirement Structural Model on the Document Requirement Definition (DRD) version 1.0, and then on version 1.1, right after the COFI-ref approach.

Table 3 present the results obtained by applying the Requirement Structural Model on each version of the DRD. The first and second columns are the quality factors acronym and its name. The third and fourth are the mean obtained for each version of the DRD calculated using Eq. (1).

Table 3. Requirement Structural Model results.

Acronym	QFs	Mean (RQ)	
		DRD 1.0	DRD 1.1
QF1	Correctness	0	0,58
QF2	Completeness	-1,27	0,32
QF3	Consistency	0,27	0,77
QF4	Clarity	0,33	0,81
QF5	Non-Ambiguity	0,67	0,97
QF6	Connectivity	0,73	0,9
QF7	Singularity	0,27	0,58

QF8	Testability	0,87	0,77
QF9	Modifiability	0,4	0,55
QF10	Feasibility	0,53	0,9

With these results we can deduce that:

a) A considerable increase in the quality factors value between the DRD versions;
b) The success of applying the Requirement Quality Metrics.

To better understand the results a discussion of each quality factor is needed as follows:

QF1 – Correctness

This attribute evaluate the absence of errors in the statement of requirement, in terms of all quality factors and/or grammatical ones, that is the DRD 1.0 shows that the set of requirement was incorrect while the its new version, DRD 1.1, have a considerable improvement.

QF2 – Completeness

This attribute evaluate if the requirement satisfy all of the information to enable the condition of its implementation and verifying process. For DRD version 1.0 the negative value obtained has its origin in omission ratio. In other words, in this version of DRD there were some requirements that are not complete generating a high score of omission ratio, which did not happens on DRD version 1.1.

QF3 – Consistency

This attribute evaluate if the requirement are not in conflict with any other, nor element of its own structure. The result shows that COFI-ref approach was able to identify precisely the elements in requirement statement.

QF4 – Clarity

This attribute evaluate if the requirement are understandable in terms of semantic analysis. The result shows that COF-ref approach could improve the requirement statement. This was possible once some of the DRD 1.0 requirements have been divided into smaller ones.

QF5 – Non-Ambiguity

This attribute evaluate if the requirement are only one semantic interpretation. The result shows that the increment of 0.3 was possible because of QF4, once one requirement statement on DRD 1.0 generates two or more requirements.

QF6 – Connectivity

This attribute evaluate if all terms within other requirements are adequately linked. The increase value in result was possible because after COFI-ref approach the requirements were better classified into the eight elements, as shown is Table 1.

QF7 – Singularity

This attribute evaluate the property of the requirement to be expressed in two or more requirements with different meanings. The increase on its value shows that the requirement statement can be more accurately classified into the eight elements, as shown is Table 1.

QF8 – Testability

This attribute evaluate if the requirement can be properly verified. This is a significant result once COFI-ref approach is part of a Verification & Validation technique. The value obtained on DRD 1.0 is higher than DRD 1.1 because of two factors: (a) new requirements were created in this last version and (b) some expression like “to be defined” was elaborated.

QF9 – Modifiability

This attribute evaluate that requirement can be changed in order to avoid any previously quality factor. The increase in value of DRD 1.1 was not higher because of the same factors presented on QF8.

QF10 - Feasibility

This attribute evaluate if the requirement is able to be satisfied within physical phenomena and applies to the project. The improvement on DRD 1.1 shows that this attribute is directly proportional to the understanding of the requirement in terms of all quality factors.

Figure 4 presents the evolution of system requirements between DRD versions. The negative value on DRD 1.0 was calculated using Eq. (3), which considers the sum of omission ratio. Though this point of view we can clearly conclude that DRD 1.1 remained in the unitary interval [0,1], showing that COFI-ref approach improve the quality of system requirements, according the Requirement Structural Model.

Next section presents a conclusion and lessons lear ITASAT-1 satellite.

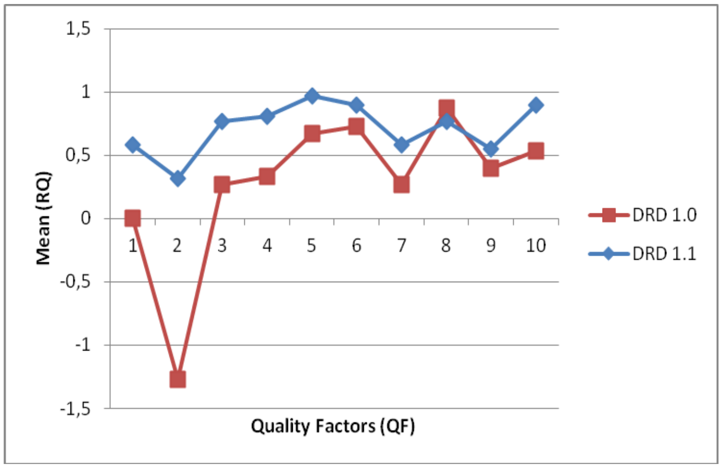

Figure 4 – System Requirements evolution through Requirement Quality Metric used.

V. Conclusion

This work presented the results obtained by applying a Requirement Evaluation Model into system requirements of the ITASAT-1 satellite, a Brazilian small-technological satellite.

It was showed that the Requirement Structural Model can be easily applied to evaluate requirements qualities, and extended to all phases of a system life-cycle. Besides that, COFI-ref approach has been successful applied to refine requirements using formal language [12]. The refinement is based on the grammar of the language that it is applied. Many authors describes the refinement through some mathematical formalism, however the use of formal methods show us that this formalism is used and one of the COFI-ref approach concern is to hidden the mathematical formalism in a way that these properties still be followed.

The cost of implementing these metrics within a suitable, according to Halligan [9] appears to be around two percent of the cost of the total requirements engineering effort.

The Lessons Learned showed us that how more the system analyst is trained more effectiveness it will be the results obtained by COFI-ref. In other words, the analyst must have at least an intermediate knowledge about the approach and the correlates techniques like: formal methods, automata theory, analysis, and system development. The Requirements management benefits substantially from the use of computer based tools which facilitate, in particular, efficient text handling, rigorous requirements allocation and the creation and maintenance of peer and parent-child relationships for requirements traceability purposes. Halligan [9] has shown that metrics prove to be most easily calculated where a CASE environment is in use for those other aspects of requirements management.

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References

[1] Ambrosio, A. M.; Martins, E.; Vijaykumar, N.L.; de Carvalho, S.V. "A Conformance Testing Process for Space Applications Software Services." *JACIC - Aerospace Computing, Information, and Communication, Vol.3, N.4, pp.146-158*. Publisher American Institute of Aeronautics and Astronautics - AIAA, April 2006, USA.

[2] Ambrosio, A. M.; Mattiello-Francisco, M. F.; Martins E. "An Independent Software Verification and Validation Process for Space Applications." *In: CONFERENCE ON SPACE OPERATIONS 9. (SPACEOPS 2008), 2008,* Hidelberg. Proceedings... 2008. p. 9. CD-ROM. (INPE-15303-PRE/10112).

[3] Best Practices Working Group of the Space Operations and Support Technical Committee (SOSTC) of the American Institute of Aeronautics and Astronautics. “Satellite Mission Operations Best Practices.” *AIAA Space Operations and Support Technical Committee (SOSTC). April, 2003*

[4] ECSS-E-10 Part 1B, Space Engineering - System Engineering - Part1: Requirements and process. 18 November 2004.

[5] ECSS-E-40 Part 2B, Space Engineering - Software - Part 2: Document requirements definitions (DRDs). 31 March 2005.

[6] ECSS-E-70 Part2A, Space Engineering - Ground systems and operations - Part2: Document requirements definitions (DRDs), 2 April 2001.

[7] ECSS-E-ST-70-11C, Space Engineering - Space segment operability. 31 July 2008.

[8] ECSS-M-ST-10C, Space Project Management - Project Planning and implementation. Revision 1, 6 March 2009.

[9] Halligan, R. “Requirements Metrics: The Basis of Informed Requirements Engineering Management.” *In: COMPLEX SYSTEMS ENGINEERING AND ASSESSMENT TECHNOLOGY WORKSHOP*, 1993, Naval Surface Warfare Center, Dahlgren, Virginia. Proceedings.

[10] IBM Corporation. “Get It Right the First Time: Writing Better Requirements.” 2008.

[11] IEEE Std. 830-1998. “IEEE Recommended Practice for software Requirements Specifications.” *IEEE Computer Society*, 1990.

[12] Morais, M. H. E, Ambrosio, A. M., “A new model-based approach for analysis and refinement of requirement specification to space operations”. SpaceOps 2010 Conference, 2010, Huntsville. SpaceOps 2010 Conference, 2010.

[13] Pontes, R. P.; Morais, M. H. E.; Veras, P. C.; Ambrosio, A. M.; Villani E. “Model-based Refinement of requirement specification: A Comparison of two V&V Approaches.” *COBEM, International Congress of Mechanical Engineering*, November 15-20, 2009, Gramado, RS, Brazil.