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A Systems Engineering approach for specifying a combined Compact Antenna Test Range and Near-Field Scanner facility

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Abstract

This paper describes a Systems Engineering (SE) approach established at the Systems Engineering Office (LSIS) to produce a system-level specification for a combined Compact Antenna Test Range (CATR) and Near-Field Scanner (NFS) facility. The Integration and Test Laboratory (LIT) of the Brazilian National Institute for Space Research (INPE) is currently expanding its facilities due to the evolution of Brazilian space programs, which include larger, complex, and heavier satellites, such as telecommunication satellites. One of the new test facilities that will be part of LIT is an integrated CATR and NFS facility for antennas and satellite payloads testing. An SE approach based on ISO/IEC/IEEE standards has been chosen to produce the required system-level specification. This tailored approach and the specific activities and results within this project are described. Additionally, this paper presents a review of several existing compact test range facilities. The LSIS systems engineering approach that was used enabled the definition of a balanced solution for the combined CATR and NFS facility that aligns with Brazilian space program projections. This new testing facility will allow INPE remaining up-to-date in the satellite testing industry while entering the large satellite industry.
Keywords: compact antenna test range; compact payload test range; near-field scanner; test facility; telecommunication satellites; dual-use range facility.

Acronyms/Abbreviations
Antenna Under Test (AUT)
Assembly, Integration, and Verification (AIV)
Compact Antenna Test Range (CATR)
Compact Payload Test Range (CPTR)
Device Under Test (DUT)
Electro-Magnetic Interference (EMI)
Electro-Magnetic Compatibility (EMC)
European Space Research and Technology Centre (ESTEC)
Geostationary Defense and Strategic Communications Satellite (SGDC)
Hybrid European RF and Antenna Test Zone (HERTZ)
Integration and Test Laboratory (LIT)
National Institute for Space Research (INPE)
National Program of Space Activities (PNAE)
Near-Field Scanner (NFS)
Space Systems Strategic Program (PESE)
Systems Engineering (SE)

1. Introduction

The Integration and Test Laboratory (LIT), inaugurated in 1987, was designed and built in order to have in Brazil the capabilities needed for the development of AIV activities from parts level to the spacecraft level [1]. LIT has supported numerous successful space missions, such as SCD 1/2A/2B, SAC C/D, and CBERS 1/2/2B/3/4 [2].

During its 30 years of operation, LIT's facilities have shown twice some limitations in terms of its capabilities to support larger and heavier satellites. This has led LIT to two extension projects.

The first extension project, finished in 2003, resulted in new capabilities such as [1]:

- 160kN vibration system.
- Large acoustic chamber.
- 6m x 8m thermal vacuum chamber.
- Larger EMI/EMC chamber.

The second extension project, started in 2012, is currently in progress and it has been the result of an analysis on the current and future Brazilian space programs [1].

The analysis was performed by LIT together with external consultancy in order to assess LIT's capabilities against the needs of the current and future Brazilian space programs, which are mainly represented by the PNAE (civilian programs) and PESE (military programs).

The analysis showed that [1]:

- The most probable scenario for the upcoming years includes telecommunication and radar satellites for both civilian and military programs.

- LIT's current capabilities are not enough to completely fulfil the AIV requirements of these type of satellites.

The breakdown of this analysis exposed LIT's needs in terms of facilities. Among these new facilities, a CATR and an NFS were identified to enable the testing of telecommunication and radar satellites, respectively. The specific project involving these two testing systems is referred herein as Compact Payload Test Range (CPTR) project, following a denomination used at ESA-ESTEC for a facility that combines these two systems.

The development of this type of projects, which involve high complexity and several players, requires a systems engineering approach. LSIS has tailored the framework and processes from the ISO/IEC/IEEE 15288 "Systems and software engineering – system life cycle processes" [3] and IEEE 15288.1-2014 "Standard for application of systems engineering on defense programs" [4] standards in accordance with LIT needs (e.g. resources, staff, and tools). The result was an SE approach focused mainly on the initial stages of development and conceptual design activities.

This paper describes the systems engineering approach that has been adopted by the Systems Engineering Office (LSIS) of LIT/INPE to define a set of system-level specification for the facilities. The system-level specification is required since the elements of these testing systems, as defined at management level, will be procured.

The following sections provide an introduction to the antenna and satellite testing facilities, the systems engineering approach established by LSIS, the results of its application for the CPTR project, a discussion about the approach and the results, and finally, some conclusions about this work.

2. Introduction to antenna and satellite testing facilities

Antennas and satellite payloads can be tested on near-field or far-field ranges. Nevertheless, for satellite applications, the measurement systems should be within clean-room environments [5].

The choice of range depends on several factors, such as directivity of the AUT; the size, weight, and volume of the DUT; the frequency range; the desired test parameters; and the costs and complexity of the test facility. [6-7]

On the one hand, near-field measurement systems can be achieved by the following alternative configurations [6]:

- Planar.
- Cylindrical.
- Spherical.

On the other hand, far-field measurement systems can be achieved by the following alternative configurations [6]:

- Outdoor range.
- Anechoic chamber.
- Compact range.

An analysis of several facilities around the world showed that most of the far-field and near-field measurement systems are built on separate rooms. According to [8], compact range and near-field systems when combined into the same room (i.e. dual-use range facility) can provide benefits, such as:

- Measurement capabilities over an extended range of frequencies.
- Test capabilities for larger antennas.
- More versatility.
- Comparative measurements.
- Shared instrumentation.
- Reduced costs when compared with the two separate systems.

Following this idea, a review was performed on compact test range facilities over the world (see Table 1 at the end of this paper) to identify previous experiences on dual-use range facilities. Table 1 shows that compact range and near-field combined facilities are unusual. The study suggested that despite its benefits, the high complexity required to build both systems together makes this option to be atypical.

An example of a dual-use range facility is the HERTZ [9] facility at ESTEC, which combines compact range and near field systems in the same anechoic room (see Figure 1).

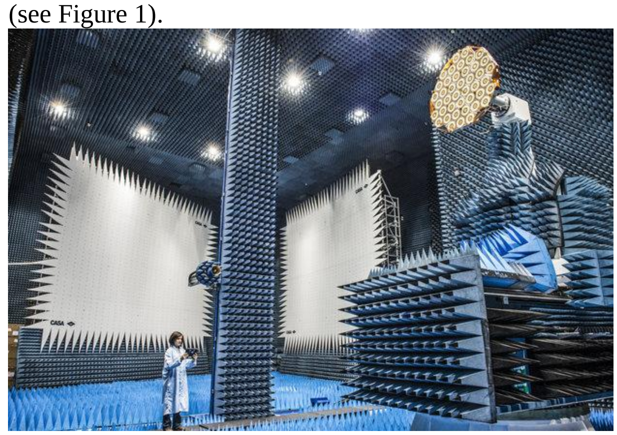

Fig. 1. HERTZ at ESTEC [10].

It should be noticed that in the HERTZ system, a near-field scanner was incorporated into an existing compact range facility [11].

3. LSIS Systems Engineering approach

LIT's Systems Engineering Office (LSIS) has adopted a Systems Engineering approach tailored from ISO/IEC/IEEE 15288:2015 standard [3]. This approach changes and simplifies the standard framework to make it suitable for LIT's structure and resources.

LSIS's SE Approach comprises mostly technical and technical management processes (Fig. 3) given that Agreement and Organizational Project-Enabling processes are already part of LIT institutional processes.

3.1 Concept definition processes

The concept definition processes targets to identify the stakeholders' needs and requirements and to achieve high-level solutions of the system to be developed that are expected to fulfil needs and requirements.

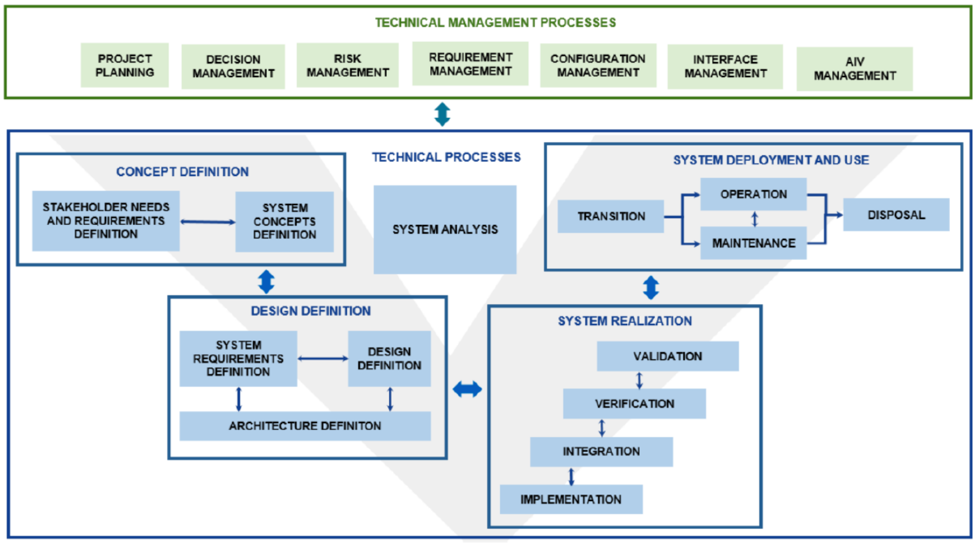

Fig. 3. LSIS's SE approach.

Furthermore, some processes were changed to ease their application in INPE and LIT's institutional context.

A major change affected the "Business and Mission Analysis Process" from ISO/IEC/IEEE 15288:2015 framework. Such process was changed to "System Concepts Definition Process" to emphasize the importance of the system concepts in the SE development effort.

As per ISO/IEC/IEEE 15288:2015, the technical processes are those that transform the needs of stakeholders into a product and service. Technical processes are comprised of concept definition processes, design definition processes, system realization processes, system deployment and use processes, and the system analysis process.

The technical management processes are those related with the management and application of the resources and assets to fulfil the agreements into which the organization enters [3]. Technical management processes include project planning, decision management, risk management, requirement management, configuration management, interface management, and AIV management.

In order to produce the system-level specification for the CPTR, the focus was put on the concept definition processes and partially on design definition processes. These processes are briefly described in the next paragraphs.

3.1.1 Stakeholder needs and requirements definition

The purpose of Stakeholder Needs and Requirements Definition Process is to define the stakeholder requirements for a system that can provide the required capabilities. By this process, systems engineers elicit and describe the needs, wants, desires, expectations, and constraints of stakeholders. The objective is to characterize the problem space and to identify the constraints on a system solution and a set of stakeholder requirements.

The following steps are recommended for this process:

a) Identify stakeholders involved with the system throughout its life cycle, and their needs;
b) Characterize the problem space;
c) Identify the expected set of use scenarios of the system;
d) Transform the information gathered from previous steps into a common set of stakeholder requirements.

3.1.2 System concepts definition

The purpose of System Concepts Definition Process is to characterize the solution space via the definition of system life cycle concepts for the system-of-interest, including the determination of potential solution class(es) from the operations concept(s). A solution space can be characterized by solution class(es), or even by a single solution. This should be subjected to the Decision Management Process.

As noted before, System Concepts Definition Process was created from the original "Business and Mission Analysis Process". The reason for that is that in the LSIS's approach all analysis processes are part of the System Analysis Processes, whereas the synthesis processes are part of System Definition Processes (Concept and Design Definitions). In addition, it was considered the criticality of concept design in every SE development as a good reason for prescribing a specific process for concepts definition.

The following steps are recommended for this process:

a) Define the business or mission problem or opportunity;
b) Characterize the solution space via the definition of system life cycle concepts;
c) Determine, from system life cycle concepts, potential solution class(es) that could address a problem or take advantage of an opportunity.

Fig. 4 illustrates how both concept definition processes described above are related to the problem and solution spaces.

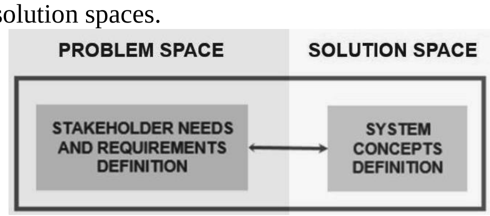

Fig. 4. Concept definition processes relationship.

3.2 Concept definition supporting processes

Concept definition is supported by design definition processes and other processes as shown in Fig. 3. It should be highlighted that due to the characteristics of the CPTR project, the design definition processes within the SE effort were limited to those needed to produce a system-level specification. Fig. 5 shows the supporting processes of the concept definition processes within the context of this project.

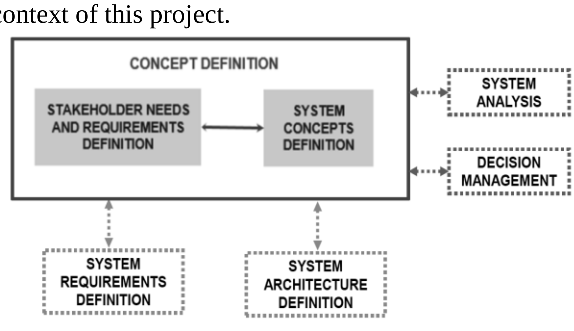

Fig. 5. Concept definition supporting processes.

3.2.1 System analysis

The system analysis process targets to provide data for the decision-making activities, enabling the comparison of alternatives and the subsequent decision. This process can be triggered by any other process at any moment.

3.2.2 System requirements definition

The system requirements definition process targets to produce a set of requirements that describes what the system shall do and have to fulfil the stakeholders' needs and requirements, in accordance with the system concept, system architecture, and the system design. Supporting concept definition, system requirements definition process produces a preliminary body of system-level requirements, mostly related with the solution classes provided by System Concepts Definition Process.

3.2.3 Architecture definition

The architecture definition process targets to develop a logical and physical arrangement of the elements that will be part of the system. System architecture is highly related with the solution classes provided by System Concepts Definition Process. During this process, several architectures can be proposed and assessed. Consequently, this process should trigger the systems analysis process and decision-making activities.

3.2.4 Decision management

According to ISO/IEC/IEEE 15288 [3], the purpose of this process is to "provide a structured, analytical framework for objectively identifying, characterizing and evaluating a set of alternatives for a decision at any point in the life cycle and select the most beneficial course of action". This process can be called anytime a technical decision is required.

4. Application of the LSIS SE approach

The SE approach previously described was executed through several activities, which led to several findings and definitions. Subsequent sections described such activities and results.

4.1 Activities

The stakeholder needs and requirements definition process included the following activities:

- Stakeholders identification (e.g. PNAE and PESE representatives, LIT's antenna tests operators, extension project chief).
- Semi-structured interviews to stakeholders.
- Documentation review (e.g. PNAE, PESE, standards, and LIT's capabilities documents).
- External consultancy.
- Identification of use scenarios and constraints.

The system concepts definition process included the following activities:

- Life cycle stages identification.
- Life cycle concepts proposal.

- External consultancy.
- Visits to antenna and satellite payload test facilities.
- Bibliographic research on near-field, far-field, and dual-use ranges for antenna and satellite payload tests.

The architecture definition process has included the following activities:

- Identification of the major elements of the system (e.g. scanner, reflectors).
- Preliminary system modelling.

The system requirements definition process has included the following activities:

- Identification of preliminary system requirements.
- Identification of critical performance measures.

The system analysis process has included activities, such as:

- Stakeholder analysis.
- Requirement analysis.
- Effectiveness analysis.
- Cost analysis.
- Technical risk analysis.
- Viability analysis.

4.2 Results

The application of the aforementioned activities led to several definitions that are briefly described in the following paragraphs.

Several stakeholder needs and requirements were identified. The most important were:

- LIT wants to be a player in the large satellite industry that may include geostationary telecommunication, meteorological, and radar satellites.
- LIT expects to be able to test satellites with at least the characteristics (e.g. dimensions, weight, frequency) of SGDC-1.
- LIT expects to be able to test radar satellites with antennas up to 12 m.

The solution space was first characterized by solution classes, such as far-field and near-field systems. Then, using the system analysis process such classes were assessed with more detail. Not only the advantages and disadvantages of the different concepts, but also other factors and constraints

On the one hand, typical implementations for telecommunication satellites tests were identified and assessed. On the other hand, typical implementations for radar satellites tests were also identified and assessed. Each alternative has certain advantages and disadvantages, involving different cost, size, and complexity details, which supports the decision of the one to be implemented [6]. Fig. 6 shows a few of the commonly used solutions for antennas and payload tests [7].

Table 2 shows an assessment of the typical near-field and far-field systems in terms of several parameters, such as frequency range, cost, complexity, and measurement speed.

It should be highlighted that not only the advantages and disadvantages of the different concepts were assessed, but also were other factors and constraints, such as the availability of resources and the characteristics of the other elements of the LIT's extension project.

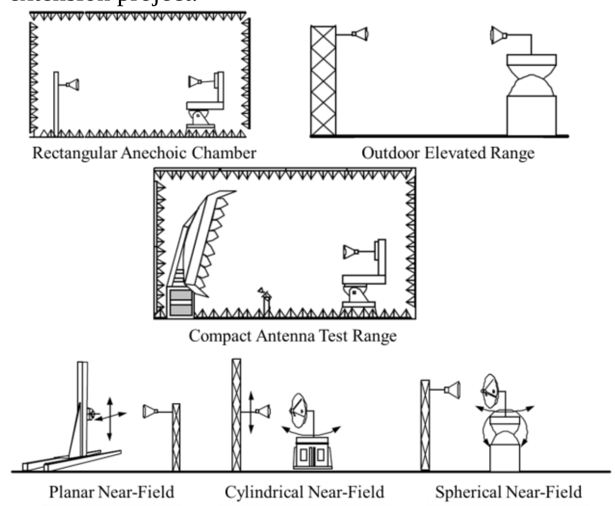

Fig. 6. Solution alternatives. Adapted from [7].

Table 2. Near-field vs far-field systems comparison. Adapted from [6].

	Near-field			Far-field		
	Planar	Cylindrical	Spherical	Outdoor range	Anechoic chamber	Compact range
High gain antenna	Ex	G	G	A	A	Ex
Low gain antenna	P	G	G	A	G	Ex
High frequency	Ex	Ex	Ex	G	P	Ex
Low frequency	P	P	G	G	F	P
Gain measurement	Ex	G	G	Ex	G	Ex
Close sidelobes	Ex	Ex	Ex	G	P	Ex
Far sidelobes	A	Ex	Ex	G	P	G
Low sidelobes	Ex	Ex	Ex	V	P	G
Axial ratio	Ex	Ex	Ex	G	P	G
Facility cost	L	M	M	H	M	VH
Operating cost	M	M	M	H	M	M
Speed	Ex	G	F	F	F	F
Complexity	M	M	H	M	L	H
Antenna access	Ex	Ex	Ex	G	G	F
Antenna alignment	Ea	M	D	M	M	D

A: Adequate. D: Difficult. Ea: Easy. Ex: Excellent. F: Fair. G: Good. H: High. L: Low. M: Moderate. P: Poor. V: Variable. VH: Very high.

A concept of a dual-use range facility combining a compact range (i.e. CATR) and a near-field system (i.e. NFS) was chosen. Specifically, a compact range system with two reflectors and a near-field system with a planar configuration were chosen for both types of systems.

The intention to build both systems together in the same room represents an enormous challenge since both systems shall share resources (e.g. physical space and instruments) without interfering (physically and electromagnetically) with each other. However, this concept is being regarded as the best in order to reduce costs and to optimize the available space for the building extension. Fig. 7 shows the current concept of LIT's CPTR facility.

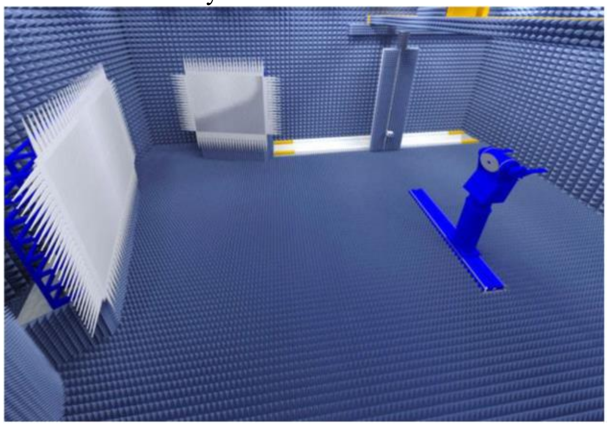

Fig. 7. Envisioned LIT's CPTR facility [1].

The CPTR facility has been decomposed into elements that will comprise the entire system. Fig. 8 shows the current visualization of the CPTR facility.

- The CPTR facility shall operate in a frequency range from 1 to 40 GHz.
- The anechoic chamber shall have a quiet zone of 5.5m x 5m x 6m (Length x Width x Height).
- The CPTR facility shall operate in a frequency range from 1 to 40 GHz.
- The CPTR facility shall be designed in such a way that the anechoic chamber is in level with its outside.
- The airflow shall avoid hot spots in the area of both reflectors.
- The clearance around the elements of the CPTR facility shall allow service access.
- The lifting shall handle not less than 15 tons (150 kN).
- The concrete foundation and floor shall be made of materials which do not allow penetration of water or moisture.
- The floor shall be made with anti-electrostatic materials.

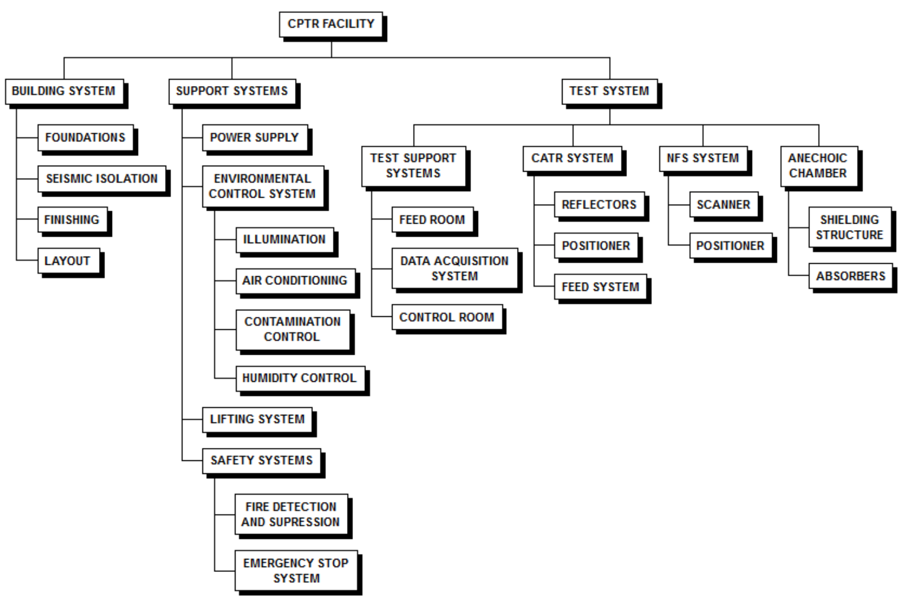

Fig. 8. CPTR facility elements.

From previous definitions, the system-level specification comprises several requirements such as:

- The CATR and NFS systems shall operate in the same anechoic chamber without interfering (physically or electromagnetically) each other.
- The anechoic chamber shall have a quiet zone of 5.5m x 5m x 6m (Length x Width x Height).
- The CPTR facility shall operate in a frequency range from 1 to 40 GHz.

Table 3 summarizes the expected main characteristics of the CPTR facility. The structure of Table 3 was done in a way that allows its comparison with other compact range facilities described in Table 2.

Table 3. LIT's CPTR facility characteristics.

Reflectors	**Size (m)**	**Quiet zone (m)**	**Frequency range**	**NFS**
2	35x20x16 (LxWxH)	5.5x5x6 (LxWxH)	1 – 40 GHz	Yes

It should be highlighted that most of the assessments that have been used within this project have been performed by systems engineers and several experts of the satellite and antenna tests industry, such as LIT's specialists on antenna tests, LIT's project management team, and external consultants.

It should be also highlighted that the described SE effort is still in progress in the third quarter of 2017. Given the recursive characteristic of the SE approach, the project is currently reviewing the concept stage. Several requirements are still To Be Confirmed (TBC) or To Be Determined (TBD). However, some elements of the system achieved a certain level of maturity and are being implemented, such as foundations. Under these conditions, the systems engineering approach gains more importance since it shall ensure that undefined elements and implemented elements do not lack of cohesion when the whole system is finally implemented.

In the near future, further activities include the procurement of some elements, such as reflectors, data acquisition system, positioner, and absorbers.

Management team has also decided that the CATR system will be first implemented in order to be available to fulfil SGDC-2 AIV campaign, which is expected to be performed at LIT. Then, in a second stage, the NFS system will be implemented to fulfil future radar satellites that are envisioned in PNAE and PESE.

5. Conclusions

The SE approach enabled the definition of a concept and the system-level specification of a test facility that is aligned with the future demands of Brazil.

With the new test facility, LIT will remain present in the satellite testing industry, and it will be up-to-date with the latest developments and trends in such industry. Furthermore, LIT will enter the large satellite industry expecting to be an option for international satellite manufacturers, providing the complete range of tests needed for AIV campaigns. The new test facility will provide LIT with the capabilities needed to test telecommunication satellites as well as radar satellites and antennas.

Even though both systems will be implemented at separate stages, the idea of conceiving the test facility taking into account requirements and constraints of the CATR and the NFS systems since the beginning of the project is expected to minimize future renovations and updates to the facility and potential incompatibilities between both systems.

Due to the concurrent and iterative features of SE approach, some of its processes are still on-going. Consequently, the partial results exhibited herein may not be final.

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Table 1. Review on compact range facilities over the world [9-53].

Organization	**City, Country**	**Technology**	**Reflectors**	**Size (m)**	**Quiet zone (m)**	**Frequency range (GHz)**	**Combined NFS**
Airbus DS	Ottobrunn, Germany	CCR 75/60	2	Not found	5.8x5.3x6	1 – 200	No
Airbus DS	Munich, Germany	CCR 75/60	2	Not found	5.8x5.3x8 (WxHxD)	1.5 – 200	No
CAST	Beijing, China	CCR 120/100	2	42x28x18	8x8x12	1 – 100	No
CAST	Xi'an, China	CCR 75/60	2	Not found	Not found	Not found	No
CNES	Toulouse, France	SCR 60	1	22x12x12	4 (D)	0.4 – 40	No
CSIRO ICT Centre	Marsfield, Australia	Not found	1	12x6x4 (LxWxH)	0.6 (D)	Up to 200	No
DLR	Wessling, Germany	Not found	2	24x11.7x9.7 (LxWxH)	3.8 (D)	1 – 100	No
ESTEC	Noordwijk, Netherlands	CCR	2	25x16x11 (LxWxH)	5x7x5 (LxWxH)	3.4 – 20	Yes
ESTEC	Noordwijk, Netherlands	Not found	2	12.5x8.5x4.3 (LxWxH)	1x1.2x1 (LxWxH)	4 – 110	No
GTRI	Atlanta, USA	Not found	Not found	18.3x7.3x5.5 (LxWxH)	1.8x1.8x1.2 (LxWxH)	2 – 100	No
IHF/RWTH Aachen University	Aachen, Germany	Not found	1	5x5x9	1.2 (D)	2 – 75	No
Intespace	Toulouse, France	CCR 75/60	2	30x20x15.5	5.5x6x8	1.47 – 40	No
ISRO	Ahmedabad, India	CCR 75/60	2	36x12x12 (LxWxH)	5.5x5x8 (WxHxD)	1 – 200	Unclear
ISRO	Bangalore, India	CCR 75/60	2	30x20x16	5.5x5x8 (WxHxD)	1 – 40	No
Kawasaki	Gifu, Japan	SCR 50E	1	Not found	Not found	Not found	No
Lincoln Laboratory	Massachusetts, USA	Not found	1	20.1x13.4x11.6 (LxWxH)	3.7 (D)	0.4 – 100	No
Mitsubishi Electric	Tokyo, Japan	CCR 75/60	2	20x30x16	5 (D)	1.5 – 100	No
Munich University	Munich, Germany	CCR 20/17	2	7x6.3x5.8 (LxWxH)	1.3x1.3x1.5	3.5 – 200	No
Ohio State University	Ohio, USA	Offset Parabolic Reflector	1	12.2x6x18.3	1.3 (D)	1 – 30	No
QMUL	London, UK	Cassegrain-Gregorian system	3	Not found	0.7 (D)	60 – 325	No
RAL Space*	Oxfordshire, UK	Not found	Not found	Not found	Not found	Not found	No
Raytheon	Massachusetts, USA	Not found	2	13.7x6.7x6.7 (LxWxH)	3.7x1.8x1.8	0.5 – 110	No
Raytheon	Massachusetts, USA	Not found	2	27.4x13.7x13.7 (LxWxH)	3.7x7.3x3.7	0.2 – 110	No
Legend: *Under construction / D: Diameter / L: Length / W: Width / H: Height / CCR: Compensated Compact Range / SCR: Single Reflector Compact Range							

Table 1 (Continuation). Review on compact range facilities over the world [9-53].

Organization	**City, Country**	**Technology**	**Reflectors**	**Size (m)**	**Quiet zone (m)**	**Frequency range (GHz)**	**Combined NFS**
Russian Systems and Technology	Moscow, Russia	Not found	Not found	Not found	2 (D)	1 – 40	No
Sameer Kolkata Centre	Kolkata, India	Not found	Not found	Not found	1.8x1.8x1.8	1 – 100	No
Selex ES	Bedforshire, UK	Not found	Not found	Not found	3 (D)	0.5 – 18	No
SSL	Palo Alto, USA	CCR 75/60	2	Not found	4.9x4.9	2 – 31	No
SUPARCO*	Lahore, Pakistan	Not found	Not found	27x19x14	5x5x6	1 – 40	No
Thales Alenia Space	Cannes, France	CCR 75/60	2	Not found	5.5x6x8 (WxHxD)	Not found	No
Turkish Aerospace Industries*	Ankara, Turkey	CCR	2	27x19x14	5x5x6	1 – 40	No
TWR	Ohio, USA	Not found	1	21x9x5.5 (LxWxH)	2.4 (D)	2 – 75	No
XLIM Institute de Recherche	Limoges, France	Not found	1	8x5x5	0.08	8 – 75	No
Legend: *Under construction / D: Diameter / L: Length / W: Width / H: Height / CCR: Compensated Compact Range							