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Systems Concepts Research Applied to Radar Design

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***Abstract* — Radar systems are usually based on complex and critical technologies, and demand solutions to attend demanding operational, functional and performance requirements, under restrictions of costs and submitted to harch environments. To create new radar systems, or even to upgrade existing radars, it is recommended to execute the concept phase of the project life cycle. The Systems Concepts Research (SCR) method was structured by one of the authors[1], and is appropriate to obtain the most adequate radar system concept to attend the needs and requirements.**

The objective of this article is to describe the phases, steps and tasks of the SCR, applied for the definition of a generic radar system, considering the most prominent characteristics of radar systems and their operational environments.

***Keywords* — research, assurance, radar.**

I. INTRODUCTION

The references [1], [2], and [3] consider the Systems Concept phase to be executed before the Systems Development phase, and the reference [4] presents the systems and products assurance technologies to be applied during all life cycle of the project. The reference [5] method, for radar systems analysis, focus on radar requirements, systems architecture and performance parameters, to be defined before the radar system development.

Those are the main elements that inspired the creation of the SCR method, with the addition and integration of the systems assurance technologies.

Principles of SCR:

The Systems Concepts Research (SCR) method comprises a series of interactive tasks. It will require specialized knowledge and skills on management and engineering of systems, requirements, risks, product assurance, costs and project planning and product development. Depending on the specific conditions of procurement and supply of systems, the work share between client and manufacturer (or supplier) will vary. Anyway, the complete composition of tasks is practically the same.

The SCR method brings great benefits on obtaining the best solution for the needs, reduction of time and costs, increase on the system assurance, performance and cost-effectiveness, and better satisfaction of customers, users and producers.

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Motivations for SCR Applied for Radar Systems:

The project of radar systems, as many other complex and critical systems, is submitted to challenging factors presented by the current environment, as suggested by [2]. These factors are the main motivations to adopt the SCR method, as follow, in the case of radar systems:

- Increasing radar systems complexities, due to:
  - More applications and interests on information about targets: polarimetry, multi-mode, multi-target, anti-jamming, countermeasure.
  - New systems and circuits solutions: MIMO, multi-radar, phased-array (digital beamforming), compact systems.
- Evolving radar technologies changes. as:
  - Solid-state analog components, permitting to implement new “all solid-state” radars and phased-array antennas.
  - Digital converters and processors, permitting to increase radar signal and data processing capabilities, to digitally implement radar functions nearer to the antenna, and to reduce the number of components.
  - The Software-Defined Radio (SDR) technology and method, applied to radar systems. [13] [14] [15]
- Extended systems life cycles, demanding for:
  - Higher reliability, availability and durable solutions.
  - Reduced life cycle costs.
- Shorter technologies life cycles, creating demands for:
  - Systems upgrading in shorter periods.
  - More versatile solutions.
- Constantly changing requirements, creating:
  - Necessity of intense efforts to understand the problem to be solved and to collect and analyze the requirements.
  - Necessity of being ready to easily modify the solutions during the life cycle.
- More emphasis on “systems” (versus components), driving to:
  - Consider the System Of Systems (SOS) and system concept as part of the project, since the beginning.
  - Define the concept from top (SOS, system) to down (units, modules, parts), as an integrated line-of-thinking engineering.

- Higher overall radar life-cycle costs, driving to:
  - Use systems and products assurance techniques, applied during the project, to create solutions with reduced acquisition and support costs.
  - Reduce hardware and increase software solutions.
- Increasing demand for mitigation and control of uncertainty and hazard risks during the project, mainly when based on new and not well mature technologies, to obtain higher availability, integrity and safety.

There is a consensus that, by using a methodology like the SCR, it is possible to obtain a cost-effectiveness balance between the economic (cost and return on investment) and technical (performance and assurance) factors. [1] [2] [3] [4]

Phases of the SCR:

The SCR method here applied consists of four steps:

- NRA - Needs and Requirements Analysis
- SCE - Systems Concepts Exploration
- SCD - System Concept Definition
- SRAA - Systems Risks and Assurance Analysis

The details of each step and tasks, applied for a generic radar system, are presented in the following.

II. NEEDS AND REQUIREMENTS ANALYSIS FOR A RADAR SYSTEM

It starts with the description of the context of the problem to be solved by using the radar system.

During this step of SCR, it is highly recommended the intense interaction and understanding between the client and developer specialists.

NRA1. VISION OF PROBLEM

- The problem of the SOS:
  - Usually, the radar will be part of a wider system, the SOS - System Of Systems, composed of communications, remote control and operation, data and image processing and other the like systems.
  - The existing problem of the SOS that is intended to be solved by the use of the radar system shall be understood.
- Motivation and context of operations:
  - What are the operational objectives and goals to be considered?
  - What are the actors and responsible for the radar system operation?
  - The context of operations may be more complex than the radar system solely, but certainly it will be based on targets detection and ranging, using radio signals.
- The problem of the radar system:
  - Looks for a radar system that will be operational, functional, feasible, and cost-effective, according to the needs.

NRA2. NEEDS ANALYSIS

- Investigations should be done to define why and how a radar system will satisfy the needs.
- What are the evidences of the needs?
- Operational objectives and goals.
- Restrictions and suppositions:
  - Restrictions and suppositions to be imposed to the radar system, its characteristics, operations and project, like type of radar, frequency bands, and transmitted power, sometimes may be known since the beginning of the project.
- Costs and schedule:
  - Costs (life cycle costs, unitary sales costs) and schedule are usually assessed at this moment.
- Owners, operators, users, actors, responsible, and other interested persons and organizations:
  - Concerning the ownership of the SOS and future radar system, it is necessary to define who are the owners, operators, users, and other interested persons and organizations, to well define responsibilities and authorities for requirements, restrictions, and suppositions and other definitions and eventual modifications.
  - Institutions that will approve, qualify or certificate the radar system shall be defined.

NRA3. OPERATIONAL ANALYSIS

<u>Mission, profiles and scenarios: [5]</u>

The details of missions, operations and functional architectures, interfaces, and environments of the radar system will be defined according to the following tasks:

- Obtain a quantitative statement of the mission of the radar system, with:
  - Operational boundaries and limits.
  - Purpose and applications of the radar system.
  - Requirements for the primary functions of surveillance and tracking.
  - Additional functions of detection and acquisition of targets.
  - Eventual multifunction and dedication to more than one mission.
  - Distinct profiles and scenarios of the mission, associated with modes of operation.
  - Additional related functions, as self-testing, training, and other special tasks.
  - Top-level radar system states requirements, covering transportation, storage, disassembling, reassembling, and others states.

<u>Deployment and usage conditions:</u>

- Determine the conditions of operational deployment and usage of the radar system:
  - Permanently fixed installation.
  - Temporary fixed installation, being transported (by roadway, waterway or airway) from one site to another.
  - Mobile installation (ground, air, water, and space vehicles).
- Determine the type of radar system and application:
  - Short range, long range coverage.

  - Sensing, surveillance, tracking.
  - Radar transmit-receive techniques (monostatic, bistatic, MIMO).

Operational concepts:

- Indicate the types and steps of the future operations of the radar system, in all their extent and details.
- Define the repartition and relationship of the parameters and operational states between the SOS elements.

Operational environments:

- Describe and quantify the space and time environmental conditions prevailing during the radar system manufacturing, transportation, operation and maintenance, considering natural and man-made sources.

Radar system architecture:

- Present the top-level composition and architecture of the SOS, as well as the composition and architecture of the radar system as part of the SOS.
- Describe the basic identification of radar system and subsystems elements and specification of the performance requirements and their relationship with the radar system functions.
- Present the main physical requirements characterization of the radar system.

Interfaces and interoperability:

- Specify the requirements for the internal and external interfaces and interoperability conditions for system and subsystems elements.
- Examine and describe the special interfaces of the radar system elements and the operational environment conditions.

Operational surveillance coverage:

- Define the space and time coverage dimensions for the operational surveillance of the radar.
- Determine the required limits of range, elevation, azimuth and eight from the radar point of view.

Targets, target cross section, and target models:

- Define and quantify the types, complexities and space and time occurrence and distributions of targets to be detected, considering:
  - Punctual targets: aircrafts, missiles, vessels, ground vehicles, and other similar.
  - Surface targets: ground (soil, vegetation), sea surface.
  - Volumetric targets: natural tropospheric structures (clouds, precipitations, air turbulences), smoke, dust, sand, particles, and clusters of insects or birds, ionospheric layers.
- Characterize the speed limits, the minimum separation among targets, clusters of targets and targets behaviors and attitudes relative to the radar.
- Describe and quantify the radar cross sections of the targets.
- Establish models of targets, including microphysical characteristics of the targets and their backscattering response according to the polarization of the incident radiofrequency signals, and the Swerling classes of statistical signal fluctuation for the targets. [5] [6] [7] [8]
- Characterize what will be considered as clutter, depending on what is considered as targets of interest and on the operational environment.
- Define the required performance of clutter and interference processing by the radar system.
- Determine if target tracks history will be required. [6]

Number of objects:

- Clarify how many simultaneous objects (targets) the radar system shall process, by surveillance, tracking, and processing, considering the timing required for those operations.

Threats:

- Classify and characterize the expected environment of threats, jammers and other kind of man-made interference for the radar system operation, according to their natures and origins.

Radar frequency:

- The frequencies of operation are extremely influent and decisive on the project of radar systems.
- Sometimes, the desired mission and operational concept determine the frequency band to be adopted by the future radar [5] [6] [7] [8]. Then, it is only necessary to know the particular conditions (requirements) about the range of values of the frequencies and about their selection and variations according to mission and operations profiles.
- If the frequency of operation is not pre-defined, it will be necessary to define it as a function of other requirements and the scope of the system. The frequencies permitted to be used by radar systems are established by international, regional and national regulations.
- The choice of the radar frequency bands is affected mainly by:
  - The radar specific applications.
  - The region of the world where the radar system will be operated.
  - The permitted frequency bands by standards and regulations.
- The radar operation frequency mainly affects:
  - The effects on the propagation and attenuation of the radar signals on the atmosphere.
  - The backscattering radar cross section of targets, clutter and other objects.
  - The backscattering power received from targets and clutter.
  - The antenna radiation diagram, main and secondary lobes and gain.
  - The Doppler frequency as a function of the radial velocity of detected targets.
  - The sampling decorrelation time of targets.
  - The Doppler radar dilemma.

Processing resources:

- Describe the types and requirements characteristics of the signal and data processing resources of the radar system.

System assurance requirements:

- Consider, quantify and allocate to the radar system elements, each of the system and product assurance requirements, considered all the life cycle of the radar system, operations and environments, comprising:
  - Risks and Cost-Effectiveness.
  - Configuration Management.
  - Rights and Penalties of Assurance and Warranties.
  - Software Assurance.
  - Quality Assurance.
  - Reliability Assurance.
  - Maintainability.
  - Safety.
  - Security.
  - Human Factors.
  - Supportability and Logistics.
  - Sustainability.
  - Others, the like.
  - Verification and Validation.
- The radar system qualification, acceptance and certification conditions and procedures must be also included.

System life cycle and cost elements:

- The main life cycle elements are to be established, concerning:
  - Date desired to start using the system.
  - Expected duration of the useful life.
  - Cycles of operation, maintenance, revision and upgrading of the system.
  - Total cost of ownership (total cost of acquisition plus the total cost of operation).
  - Number of radar systems to be deployed.
  - Logistic support organization.

NRA4. FUNCTIONAL ANALYSIS

Radar system functional concepts: [5]

- Define the functional modes and parameters, their repartition and relationship between the SOS elements.
- Establish the role of the radar system on the SOS context.

Functional requirements:

- Describe the functions of the radar system and subsystems.

Functional allocation to radar subsystems:

- Allocate the functional requirements to the radar system and subsystems.

Functional radar performance requirements:

- Establish the main criteria for measuring the quality of performance of the radar system, in adverse environments, as [7]:
  - Reliability of detection: maximum detection range and probability or percentage of time that the desires targets will be detected.
  - Accuracy, measured with respect to target parameter estimates: target range, angular coordinates, range and angular rates and accelerations.
  - Ambiguity: the extent to which the accuracy parameters can be measured without ambiguity or the difficulty encountered in resolving any ambiguity.
  - Resolution: degree to which two or more targets may be separated in one or more spatial coordinates, in radial velocity or acceleration.
  - Discrimination: the ability to detect or to track a target echo in the presence of environmental echoes (clutter).
  - Immunity to threat: the capacity to sustain the operations when submitted to electronic countermeasure or jamming menaces.
  - Immunity to electromagnetic interference: the capacity to sustain the operations when submitted to friendly radiofrequency interference.

Functional simulation:

- Create a functional model of the radar system and subsystems.
- Create a realistic measurement error model.
- Analyze the functioning with the model.
- Include the performance characteristics in the model and analyze their effectiveness.

NRA5. FEASIBILITY DEFINITIONS

Evaluation of radar systems currently available solutions:

- Collect data about current radar systems, similar to the radar system under analysis.
- Assess the details about the used technologies.

Comparison of radar solutions and radar requirements:

- Analyze and compare the specifications of the existing solutions with the requirements for the new radar system.

Evaluation of feasibility of radar systems functional concepts:

- Evaluate if the technologies of the current solutions will permit to obtain the required functions and performances.
- Describe the needs for other technologies to attend the functional concepts.

NRA6. NEEDS VALIDATION

- Verify the evidences of the needs.
- Analyze the viability of needs attendance.
- Validate the needs and systems concepts relationship.

NRA7. OPERATIONAL REQUIREMENTS SYNTHESIS

- Elicit, analyze and validate all radar system operational requirements and constraints.

III. SYSTEMS CONCEPTS EXPLORATION FOR A RADAR SYSTEM

Taking the NRA results into account, it is necessary a detailed revision and analysis to consolidate the requirements and constraints, and to prepare a complete and integrated functional and performance model to be used as a background, and to generate various alternatives of radar system concepts.

SCE1. OPERATIONAL REQUIREMENTS ANALYSIS

- Critical analysis and revision of the radar system operational objectives.
- Detailed revision and analysis of the radar system operational concept and requirements:
  - With diagrams and models.
  - Consolidating them in a complete non ambiguous and consistent list, using, if possible, appropriate tools.
- Feasibility analysis of the radar system operational requirements:
  - Verify how each of the radar system operational requirements could be executed, considering modes, constraints and functions.
  - If any inconsistency arises, turn back to the NRA step to better understand the concepts and requirements and to remove the inconsistency.

SCE2. PERFORMANCE REQUIREMENTS FORMULATION

- Derivation of radar subsystems functions and performance requirements:
  - Consistently with each function and mode of operation of the radar system, based on the results of the previous analysis and reviews of NRA.
- Formulation of radar system and subsystems performance characteristics:
  - Develop functional and performance radar models to evaluate the theoretical and practical viability of accomplishment of the functional performance, by:
    - ✓ Using the radar equation and other relation among the characteristics already established.
    - ✓ Exploring different radar parameters and features.
- Derivation and formulation of radar system and subsystems performance characteristics.

<u>General system architecture</u>

- Before exploring the complete solutions of the radar system, it is recommended to explore the radiofrequency front-end of the system, as a basis for the other radar elements.
- The principles and techniques of SDR - software-defined radio apply also to software-defined radar. Besides elimination of hardware elements (cost reduction, greater reliability, etc), it gives much more flexibility, increase functionalities, and permit adaptation to environments and missions.

<u>Receiver performance analysis [5] [6] [7] [8] [9] [10] [11]</u>

- Create a model of the internal and external losses.
- Create a model of the noise temperature of the receiving front-end of the radar, considering:
  - Expected noise temperature environment, comprising the natural and man-made noise sources external to the system.
  - Evaluate the expected range of noise temperature from the antenna and other radiofrequency elements of the receiving circuit.
  - Evaluate the best available technologies to provide receiver front-end elements (amplifiers, filters, protections) in the radar system frequency bands, with minimum inherent noise factors, to be considered in the models.
  - Based on the previous evaluations, calculate the system noise temperature.
- Create a model of the MDS - minimum detectable signal for the receiving front-end, considering:
  - Frequency bandwidth and form factor of the receiver filter.
  - Frequency bandwidth of the receiver signal, after filtering.
  - Minimum SNR - signal-to-noise ratio at the output of the receiver.
  - The Boltzmann´s constant.
  - Calculate the minimum value of the received radar signal at the receiver input, capable to be processed and detected by the subsequent radar receiver channel circuits.

<u>Transmitter performance analysis: [5] [7] [8]</u>

- Create a model for the analysis of the performance of the radar during transmission, considering:
  - Radar frequencies of operation.
  - Peak power.
  - Modulations.
  - Average power.
  - PRF - pulse repetition frequency.
  - Pulsewidths.
  - Bandwidths.

<u>Antenna performance analysis: [5] [7] [8]</u>

- Create a model for the representation and analysis of the performance of the antenna, considering:
  - Antenna technology, format (reflector, phased array, aperture, beam forming) and dimensions.
  - Antenna radiation diagram (main lobe, sidelobes, nulls, boresight, and gain).
  - Antenna beamwidth (pencil beam, fan beam, multi beam).

SCE3. IMPLEMENTATION CONCEPTS EXPLORATION

- Assessment and analysis of radar technologies and systems possibilities:
  - Before describing specific complete radar systems, the available technologies of hardware and software usual for those types of systems must be assessed and evaluated. This will give an updated view of the possibilities, inspire innovations and reinforce the knowledge of systems architecture.

<u>Elements of the radiofrequency front-end:</u>

  - Based on the previous analysis about radar type, frequency, space resolution, radiation diagram, mobility, coverage, etc., the type and general dimensions of the antenna and antenna-transceiver coupling circuits can be selected.

- Based on the receiver performance analysis, describe alternatives of receiver front-end (LNA, filter, COHO, mixer), and analyze the characteristics (gain, dynamic range, MDS, SNR, band pass, IF, etc) of each solution.
- Considering the radar frequency, antenna gain and diagram, space coverage, targets, threats, interferences and atmospheric effects, and losses, estimate the minimum transmitter output peak power.
- Describe the alternatives of transmitter technologies (solid state, tubes, etc) and solutions (oscillator, linear amplifier, etc), and analyze their characteristics.
- Define the transmission modulation techniques, considering the peak and medium power, PRF, detection performance, etc.
- Examine the characteristics of the transmitter driving signal: frequency, power level, synchronism signals, etc.
- Define the characteristics of duplexer, antenna coupler, RF line, power supplies and control elements.

Elements of the digital processing subsystem:

- Up and down converters circuits.
- ADC/DCA circuits.
- DSP, CPU, FPGA, memories, interfaces.
- Software modules with radar functions and signal processing based on SDR techniques and practices. [12]

Elements of the visualization and networking subsystem:

- Computers, servers, network interfaces, data storage technologies, human-systems interface.
- Software for data processing, product generation and visualization, radar networking, local and remote control and operation.

- Formulation of alternatives of radar implementation concepts:
  - Considering the technologies and the functional and performance analysis, create alternatives of systems concepts possible to be implemented.
- Execution of radar elements proof-of-concepts experiments:
  - When necessary, construct models or physical elements to be submitted to tests and proof-of-concept evaluation.
- Evaluation of exequibility of radar system alternatives.
- Evaluation of the performance and the cost-effectiveness characteristics of each radar system alternative.

SCE4. PERFORMANCE REQUIREMENTS VALIDATION

- Definition, integration and validation of the radar system performance characteristics.

SCE5. PERFORMANCE REQUIREMENTS SYNTHESIS

- Description, classification and qualification of each radar system alternative.
- Synthesis of the radar system alternatives performance requirements.

IV. SYSTEM CONCEPT DEFINITION FOR A RADAR SYSTEM

SCD1. PERFORMANCE REQUIREMENTS ANALYSIS

- Analysis and refinement of performance and functional requirements of the radar system concept alternatives.

SCD2. FUNCTIONAL ANALYSIS AND FORMULATION

- Definition and simulation of the functional components of the radar system concept alternatives.
- Modeling and demonstrations with prototypes of the radar system concept alternatives.

SCD3. IMPLEMENTATION CONCEPT SELECTION

- Selection of the preferred radar system concept.

SCD4. CONCEPT VALIDATION AND DESCRIPTION

- Modeling of selected radar system concept and its environment.
- Functional and architectonic specifications of the selected radar system concept.
- Selected radar system concept validation and description.

SCD5. SYSTEM DEVELOPMENT PLANNING

- Planning for the life cycle of the selected radar system concept:
  - Planning for the development.
  - Planning for the production.
  - Planning for the support and logistics.
  - Planning for the use.
  - Planning for the discard and substitution.

V. SYSTEMS RISKS AND ASSURANCE ANALYSIS FOR A RADAR SYSTEM

SRAA1. SRAA DURING NRA

- Classification of risks of hazards and uncertainties.
- Definition of analysis criteria.
- Assessment and evaluation of the potential risks for the project, the system, and the operations.
- Evaluation of the risks derived if the radar problem will not be solved.
- Assessment, limits characterization, and evaluation of the main system assurance requirements, comprising:
  - Configuration management, verification and validation, software assurance.

- Quality, reliability, maintainability, safety, security, human factors, supportability and logistics, sustainability, and other analogous.

- Preliminary evaluation and analysis of the TCO - Total Cost of Ownership perceived by the market.
- Go-No Go decision.

SRAA2. SRAA DURING SCE

- Evaluation and comparison of risks and system assurance parameters of each alternative of system concept.
- Assessment of the availability and disclosure of parts and technologies from foreign suppliers.
- Analysis and evaluation of each trade-off solutions:
- Analysis of viability of accomplishment of the assurance requirements and cost-effectiveness balance.
- Go-No Go decision.
- Recommendations for the mitigation and control of risks and for provisioning of systems assurance and cost-effectiveness.

SRAA3. SRAA DURING SCD

- Detailed analysis, description and recommendation for mitigation and control of risks, system assurance and cost-effectiveness elements of the selected radar system concept.
- Final Go-No Go decision.

If the final decision is to proceed with the radar system development, the results obtained during the SCR phase shall be documented and transferred to the next phase of Development of Systems and Products (DSP).

VI. CONCLUSIONS

The example of application of the Systems Concepts Research (SCR) method to the case of a generic radar system concept was performed and resulted on a careful and complete analysis of the problem, the needs and the operational, functional and performance requirements.

It was also possible to demonstrate how to integrate the risks, cost-effectiveness and assurance analysis to each step of the SCR for a radar system concept.

The sequence of tasks to select and define the most appropriate radar system concept was demonstrated.

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