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Intelligence, Surveillance and Reconnaissance System Performance

Evaluation Using the Analytical Hierarchy Process

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Intelligence, Surveillance and Reconnaissance System Performance Evaluation Using the Analytical Hierarchy Process

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Abstract

Intelligence, Surveillance and Reconnaissance (ISR) systems form the backbone of any military defence and security operation. These systems, be they ground-, sea-, air- or space-based, do so by providing enhanced situational awareness to the military decision makers at the tactical, operational and strategic levels. Whereas traditional surveillance systems operate within one environment and at one level, current military requirements and technological advances have evolved to multi-domain, multi-level sensor systems. For example, Space-Based System (SBS) technology has been advancing rapidly in terms of capability, affordability, size and reliability. As in the commercial sector, defence and military institutions are looking to improve their space capabilities by increasing the number of smaller, more affordable and more capable satellites that are being put into service. Given the complexity this introduces, one of the current challenges in this area is to objectively evaluate the effectiveness of a given collection of surveillance systems (i.e., ISR architecture) to the military decision maker. This effectiveness can only be assessed by taking into account a multitude of factors – from geospatial and temporal to information and fusion, all of which combine to describe the military utility of a given architecture. This report presents an end-to-end method for assessing the utility of different ISR architectures from engineering-level simulation and modelling to the evaluation of military Figures of Merit/Measures of Effectiveness. As a proof of concept, a maritime domain awareness scenario is used in this report to evaluate the improved effectiveness of surveillance capability by the addition of an SBS to a current available ISR architecture.

Résumé

Les systèmes de renseignement, surveillance et reconnaissance (RSR) forment l'épine dorsale de toute opération de défense et de sécurité militaire. Ces systèmes, qu'ils soient terrestres, navals, aériens ou spatiaux, fournissent une connaissance de la situation améliorée aux preneurs de décisions militaires aux niveaux tactique, opérationnel et stratégique. Les systèmes de surveillance traditionnels fonctionnent dans un seul environnement et à un seul niveau, mais les besoins militaires et les évolutions technologiques ont conduit à la création de systèmes multidomaines et multicateurs. Ainsi, les technologies de systèmes spatiaux ont évolué rapidement du point de vue des capacités, de l'économie, de la taille et de la fiabilité. Comme dans le secteur commercial, les établissements de défense et les institutions militaires cherchent à améliorer leurs capacités spatiales en mettant en service un nombre plus élevé de satellites plus petits, plus économiques et plus puissants, ce qui entraîne une augmentation de la complexité. Un des défis actuels dans le domaine est donc d'évaluer objectivement l'efficacité d'un ensemble donné de systèmes de surveillances (architecture RSR) pour le preneur de décision militaire. Cette efficacité ne peut être évaluée qu'en tenant compte d'une multitude de facteurs – qui vont des facteurs géospatiaux et temporels à ceux liés à l'information et à la fusion – dont la combinaison permet d'indiquer l'utilité militaire d'une architecture donnée. Le présent rapport expose une méthode bout-en-bout pour évaluer l'utilité de différentes architectures RSR, de la modélisation et simulation au niveau ingénierie jusqu'à l'évaluation des facteurs de mérite et mesures de l'efficacité militaires. Afin de valider le concept, un scénario de connaissance de la

situation du domaine maritime est utilisé pour évaluer l'amélioration de l'efficacité d'une capacité de surveillance par l'ajout d'un système spatial à une architecture RSR actuellement disponible.

Executive summary

Intelligence, Surveillance and Reconnaissance System Performance Evaluation Using the Analytical Hierarchy Process

Rahim Jassemi-Zargani; Sean Bourdon; Van Fong; DRDC Ottawa TM 2011-224;
Defence R&D Canada – Ottawa; July 2013.

Introduction or background: Today's militaries rely on accurate and timely sensor data to conduct increasingly complex operations. Intelligence, Surveillance and Reconnaissance (ISR) systems have become essential in ensuring that objectives are met. Regardless of the environment in which they are situated, these systems empower decision makers in the defence and security realms at the tactical, operational and strategic levels. Modern militaries have become increasingly exigent in their requirements for ISR systems, calling for multi-domain, multi-level situational awareness. Technological advances have enabled significant gains on this front; however, a significant challenge in this area is to objectively evaluate the effectiveness of a collection of ISR sensors, otherwise known as an ISR architecture, in assisting with military missions. This assessment can account for a multitude of factors that range from geospatial and temporal aspects to issues with processing and fusing incoming sensor data. The goal of this report is to present a method for performing this type of evaluation. The method relies on a hierarchical decomposition of high-level objectives into Figures of Merit (FOMs) until they are easily measurable using modelling and simulation tools. The method is illustrated using the integration of Space-Based Systems into an existing baseline ISR architecture to assess its benefit to the military commander.

Results: Using the proposed method, the report shows the benefit of adding different satellite constellations which vary in size and configuration. It shows how much closer the system gets to achieving the requirements compared to the baseline system. Both the baseline sensors and the additional sensors help to offset each other's disadvantages, while creating a robust surveillance system architecture that provides an enhanced strategic and tactical capability for military operations. The augmented architecture comprises a unique intelligence-gathering tool and is well suited to combat emerging threats. Ultimately, questions about which configuration is best-suited to a particular set of missions may require additional analysis. When combined with the system costs, the Measure of ISR Effectiveness (MOIE) can be used as the basis of a cost-benefit analysis whose goal is to identify which solutions should form the cornerstone of any future ISR architecture.

Significance: The method presented herein is extendable beyond the example on which it is applied. The method is traceable, repeatable and customizable, allowing it to be adapted as needed. As such, it can be used to enable senior decision makers to advocate for specific capabilities that will best ensure that they have the information they require to successfully accomplish their missions. The hierarchical decomposition that is at the heart of the method allows for meaningful comparison of FOMs, which helps ensure that the subsequent aggregation appropriately reflects desired objectives.

Future plans: Having developed the method, future development can continue down two separate paths. The first consists of incorporating the method into a toolset that automates the

analysis and evaluation processes. This toolset will need to be integrated to work seamlessly with a modelling and simulation environment for ease of use and to allow various ‘what if’ scenarios to be examined. Part of this integration should additionally consist of further identifying a full set of representative FOMs across all levels to help ensure that the method provides the information that was desired. The second path for future work consists of verifying and validating any conclusions obtained using this method using real world trials or military exercises where possible to provide additional fidelity regarding actual system performance before making significant investments.

Sommaire

Intelligence, Surveillance and Reconnaissance System Performance Evaluation Using the Analytical Hierarchy Process

Rahim Jassemi-Zargani; Sean Bourdon; Van Fong ; DRDC Ottawa TM 2011-224
; R & D pour la défense Canada – Ottawa; juillet 2013.

Introduction ou contexte : Les forces armées d'aujourd'hui font appels à des données de capteurs exactes et disponibles en temps utile pour conduire des opérations de plus en plus complexes. Les systèmes de renseignement, surveillance et reconnaissance (RSR) sont devenus essentiels pour assurer l'atteinte des objectifs. Peu importe l'environnement où ils se trouvent, ces systèmes donnent aux preneurs de décisions militaires les moyens dont ils ont besoin dans les domaines de la sécurité et de la défense aux niveaux tactique, opérationnel et stratégique. Les forces armées modernes ont des exigences de plus en plus serrées à l'égard leurs systèmes de RSR : elles ont besoin d'une connaissance de la situation multidomaines et multiniveaux. Des développements technologiques ont permis de réaliser des gains importants sur ce plan, mais il reste cependant difficile d'évaluer objectivement l'efficacité d'un ensemble de capteurs de RSR (ce qu'on appelle une architecture de RSR) pour appuyer les missions militaires. Cette évaluation peut tenir compte d'une multitude de facteurs, qui vont des aspects géospatiaux et temporels aux problèmes de traitement et de fusion des données reçues. Le présent rapport vise à exposer une méthode pour réaliser des évaluations de ce type. La méthode fait appel à la décomposition hiérarchique des objectifs de haut niveau en facteurs de mérite jusqu'à ce que ceux-ci soient facilement mesurables à l'aide d'outils de simulation et de modélisation. La méthode est illustrée au moyen de l'intégration d'un système spatial à une architecture RSR de base existante en vue d'évaluer les bénéfices que peut en retirer un commandant militaire.

Résultats : À l'aide de la méthode proposée, le rapport montre l'avantage d'ajouter différentes constellations de satellites dont la taille et la configuration varient. Il indique dans quelle mesure le système parvient à s'approcher des exigences par rapport au système de base. Les capteurs de base et les capteurs additionnels sont complémentaires : les avantages des uns compensent les inconvénients des autres, et l'ensemble forme une architecture de système de surveillance robuste qui assure une capacité stratégique et tactique améliorée pour les opérations militaires. Avec l'ajout du système spatial, l'architecture constitue un outil de collecte de renseignement unique qui est bien adapté à la lutte contre les menaces émergentes. En fin de compte, déterminer quelle configuration est la mieux adaptée à un ensemble de missions pourrait nécessiter une analyse supplémentaire. Si on la combine au coût du système, la mesure de l'efficacité RSR peut servir de base à une analyse coût-bénéfice visant à déterminer quelle solution devrait servir de fondement à toute architecture RSR future.

Importance : La méthode présentée ici peut être étendue à des situations autres que celle de l'exemple à laquelle elle a été appliquée. Le fait qu'elle est traçable, répétable, et modifiable permet de l'adapter selon les besoins. Elle peut donc être utilisée pour permettre à des preneurs de décision de haut rang de préconiser les capacités particulières qui leur offriront l'information dont ils ont besoin pour accomplir leurs missions. La décomposition hiérarchique qui fonde la méthode permet de faire une comparaison juste des facteurs de mérite, ce qui contribue à ce que leur agrégation ultérieure reflète correctement les objectifs désirés.

Perspectives : La méthode ayant été mise au point, les recherches futures peuvent prendre deux avenues distinctes. La première consiste à incorporer la méthode à un ensemble d'outils d'automatisation des processus d'analyse et d'évaluation. Cet ensemble d'outils doit être intégré de façon transparente à un environnement de modélisation et de simulation en vue d'en rendre l'utilisation facile et de permettre d'examiner divers scénarios hypothétiques. Cette intégration devrait comprendre l'établissement d'un ensemble complet de facteurs de mérite représentatifs à tous les niveaux afin de veiller à ce que la méthode fournisse bien l'information désirée. La deuxième avenue consiste à vérifier et à valider les conclusions obtenues au moyen de la méthode grâce à des essais pratiques ou des exercices militaires, dans la mesure du possible, dans le but d'obtenir une plus grande fidélité à l'égard de la performance réelle d'un système avant de réaliser des investissements importants.

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1 Introduction

The tools and techniques used in modern military missions have evolved over the past 20 years with the primary objective to improve the efficiency and timeliness with which their forces progress between the Sense and Act functions (i.e., the Sensor-to-Shooter Cycle). Traditionally, different ISR systems were developed to be stand-alone, having their own proprietary methods of storing and disseminating information, and as such, did not easily lend themselves to information sharing. These initial architectures were followed by the development of the Command, Control, Intelligence, Surveillance and Reconnaissance (C2ISR) framework that improved war-fighting capabilities through predictive battle-space awareness utilizing a network-centric infrastructure [1]. Deploying such sensor networks (including Space, Air, Sea, Ground and Cyberspace) is a solution that enables commanders to rapidly generate battle-space awareness and improves the efficiency and accuracy between the Sense and Act capability domains. Continuing military initiatives to further improve the Intelligence Cycle have led to the development of the Command, Control, Communications, Computers and ISR (C4ISR) paradigm, with an objective to produce a “common picture” of the battle-space. The military envisions that such an architecture would be integrated, interoperable and will “jointly” cover the end-to-end process of all ISR assets. To fully realize a complete C4ISR implementation, limitations of current ISR architectures (such as limited sensor access, limited communications bandwidth, stove-pipe exploitation workstations and lack of interoperability with coalition partners) need to be overcome. To address these limitations, the military has begun investigating designs and sensor capabilities that provide a wide range of scale, resolution and timeliness of the information. This report proposes an evaluation method to determine an overall measure of system effectiveness for different ISR architectures.

To illustrate how to assess the improved mission performance when new ISR systems are added to an existing ISR capability, this report proposes a hierarchical evaluation method. For this example, the authors used the SBS as the new ISR capability. The roles of SBS (Space Based System) have been changing not only due to technological advances, but also due to the complex issues of today’s security environment, where an ISR asset is required to support military operations in a matter of hours or even minutes anywhere in the world. The number of operational SBS has been increasing rapidly in the last 30 years, but this increase has also raised a number of issues: increasing amount of man-made debris in space, increasing complexity in space asset management, increasing data handling requirements, etc. All of these changes are driven by technology advances, increasingly demanding military operational goals, and the high rate of systems development and launch capability. Integrating these changes into existing systems requires an in-depth evaluation and analysis not only on the engineering aspects of these changes during development, but also on how these systems can improve the overall defence capability that is required to satisfy current and future ISR goals [2].

Improve commander’s confidence level in decision making process by accessing the best available capabilities Full implementation (100%). This report presents a method that relies on a hierarchical decomposition of the military objectives into lower-level measures of performance (MOPs). The MOPs are combined using weights obtained through subject matter evaluation of their relative importance using Saaty’s Analytic Hierarchy Process (AHP) [3]. This report presents the initial studies and results of the AHP method and the processes that have been

developed to evaluate the military effectiveness of space-based systems and their overall impact to military ISR operations.

The remainder of this document is structured as follows. Chapter 2 provides additional background information on ISR sensor architectures. The performance evaluation method is developed in Chapter 3 and then used to evaluate the benefit of adding SBS to an existing baseline architecture. The conclusions of the report are given in Chapter 4.

2 ISR sensor architecture

Intelligence can be defined as “information and knowledge obtained through observation, investigation, analysis or understanding” [4]. Surveillance is systematic observation to collect whatever data is available, while reconnaissance is a specific mission performed to obtain specific data [5]. Within other extensions of the ISR concept, namely C2ISR and C4ISR, considerable research has been conducted to investigate how to allocate and identify sources within the latter’s functionality to maximize mission effectiveness [1,2].

2.1 ISR sources – definition

ISR systems have many different types of sensors, yet they all aim to provide accurate information on objects within an area of interest. Examples of types of sensor systems include: radar (microwave, radio wave, etc.), electro-optical (EO), infrared (IR), synthetic aperture radar (SAR) and multi-spectral imagery (MSI).

2.1.1 Baseline ISR assets

Baseline ISR assets determine the capabilities that are all currently available and can be utilized to help protect sovereign land, borders and coasts, both during peacetime and war. The baseline architecture used for this evaluation included a single airborne platform carrying a maritime radar for surface target detection and two ground-based beyond-line-of-sight radars to detect vessels beyond the visual horizon.

2.1.2 New ISR assets

New ISR assets refers to candidate sensor systems that military decision makers are considering employing to augment the capabilities of the baseline ISR architecture. These new systems may be at various stages of development or may already be in the acquisition cycle awaiting operational employment. Nonetheless, these systems all need to be evaluated for their potential contribution to the baseline ISR performance. In this report, the SBS sensor was added to achieve a persistent and non-intrusive surveillance capability. The SBS is an ISR system capable of providing Surface Moving Target Indication (SMTI), imagery and Digital Terrain Elevation Data (DTED) over a large portion of the Earth. SBS has been proposed for a variety of military and civilian applications including wide-area surveillance, theatre defence, disarmament monitoring, remote sensing, civilian air-traffic control, space exploration and law enforcement [6].

2.2 ISR architecture capabilities

One of the main issues concerning ISR architectures is the ability to move data from the reconnaissance platform to the user. There are also issues associated with ISR sensors which can impact the quality of the observed data, the time needed to gather the data, and the time to disseminate the data to the command and control centre. In the literature, many terms have been defined to characterize these capabilities, such as: early warning, wide-area surveillance, deep

look, coverage, distortion, response time, exposure to threat, vulnerability, detection, tracking, multi-area surveillance, change detection, etc. The exploitation tools such as fusion, tracking and others are used to convert the raw data to tactical and strategic products. These products will be provided to the C2 workstation based on the operator's requests.

3 Performance evaluation method

The evaluation of ISR system performance can only be accomplished by taking into account a multitude of factors, all of which combine to describe the military utility of a given architecture. An end-to-end method for assessing the utility of different ISR architectures from engineering-level modelling and simulation to the evaluation of military FOMs and MOEs is required. Such a method has been developed and is described in the following sub-sections.

3.1 General overview of the methodology

The process for evaluating ISR assets is shown conceptually in Figure 1. The evaluation will assess the performance of a new system in conjunction with other ISR systems using selected metrics to see how well mission requirements are being met. The process is divided into four steps, as shown in Figure 1:

1. ISR systems selection

Select individual ISR systems based on their capability to address mission requirements. For example, if the mission requirement is to detect and track maritime vessels, then ISR systems (e.g., sensors) that have this capability are considered candidates. In this report, we consider ground-based systems, airborne systems as well as space-based systems.

2. Mission metrics development

Identify the metrics required for the performance evaluation of ISR systems and assess their individual weights. For example, performance metrics relevant to maritime detection and tracking might include the probability of detection of maritime vessels, the ability to track a vessel over time, etc. (Note that these performance metrics apply to a suite of ISR systems as a whole, not to individual systems.)

3. ISR systems mission modelling

Model the scenarios and systems to collect the data required to evaluate the system against each performance metric. For real-life trials of ISR systems, consideration must be given to the placement of monitoring equipment to record the data required to evaluate the performance metrics (e.g., recording Global Positioning System (GPS) positions of each target vessel during a live trial).

4. ISR systems performance evaluation

Aggregate the results of all performance metrics to evaluate the overall performance of different ISR system mixes, based on the evaluations obtained during the modelling and the weights for each metric.

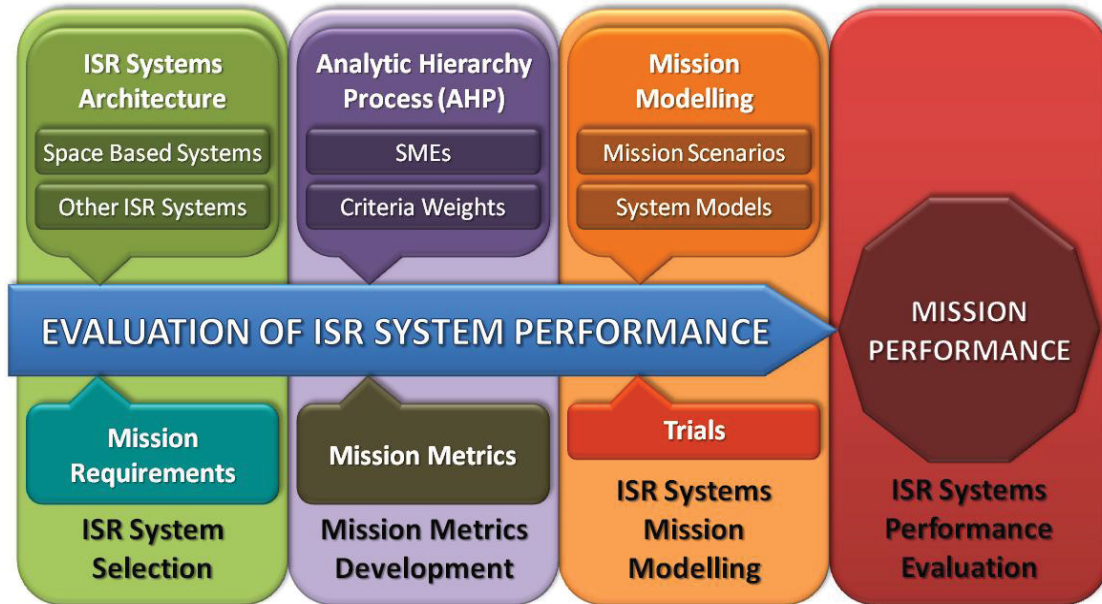


Figure 1 Assessment and modelling process

3.2 ISR system selection

The ISR system selection process begins with an expression of military mission requirements. These requirements are usually formulated in very high-level language (e.g., “Detect and track all maritime vessels within x nautical miles from national coastline). In the course of this methodology, the high-level mission requirement will be further broken down into specific and measurable mission metrics. In this first step, the high-level requirements are sufficient for identifying which candidate ISR systems/assets are selected for consideration in this performance analysis. ISR system selection is important in order to keep the number of options that need to be considered to a workable set of alternatives, and is necessary in order to prevent the complexity of the modelling and assessment phase to become unmanageable.

3.3 Mission metrics development

Mission metrics development consists of two activities: (1) the identification and selection of mission metrics with which to evaluate ISR system performance; and (2) the determination of appropriate weighting factors for each metric, which enables the aggregation of ISR system performance scores into a single measure of effectiveness. The activities are described in following sub-sections.

3.3.1 Selecting mission metrics

As mentioned previously, the metrics for the evaluation are selected based on the military requirements. The first stage is to decompose the mission requirements into one or more essential elements or factors. In the example given here, the mission requirement is to detect and track all maritime vessels within areas of responsibility. To decompose this into sub-components, the authors considered military doctrine (the ISR Cycle) and strategic level documents relating to surveillance [7]. From this, the mission requirement was broken down into six factors for performance evaluation: Tasking, Detection, Tracking, Processing, Exploitation and Dissemination. These factors, which have been designated as Figures of Merit (FOMs), make up the first level of criteria which will be used to evaluate ISR system performance.

In general, the FOMs can again be decomposed further into secondary sub-criteria in much the same way that the mission requirement was initially partitioned. For this report, the sub-criteria were selected based on operational requirements and also the ability/availability of making measurements from real-world trials.

Figure 2 illustrates the decomposition of a mission requirement into criteria and sub-criteria; it also shows a sample of possible ISR combination options that might be considered for evaluation. The baseline capability refers to existing and available systems.

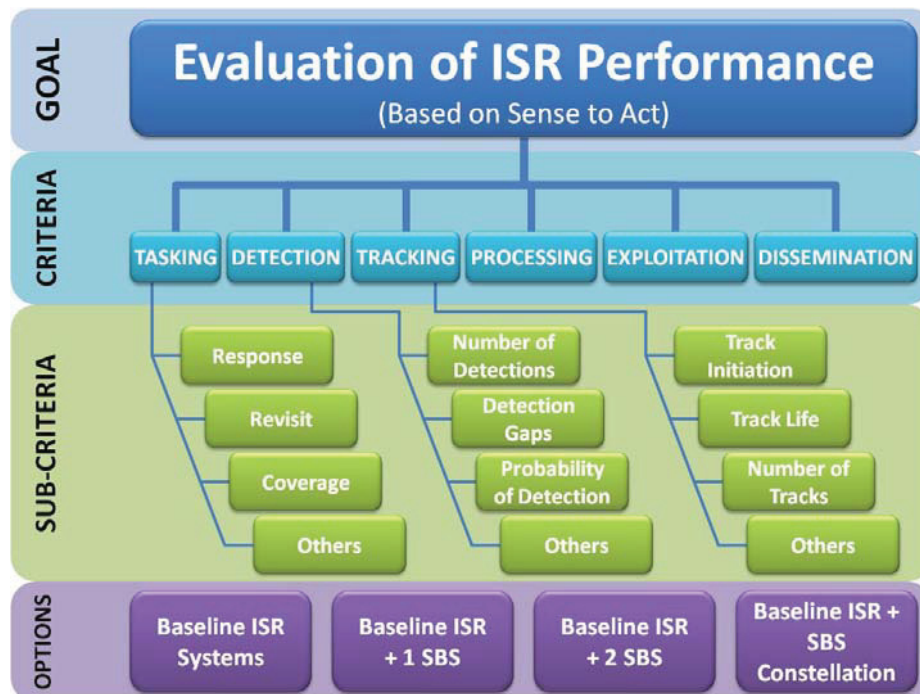


Figure 2 ISR performance evaluation process tree

3.3.2 Determining weighting factors – the Analytic Hierarchy Process

For the distribution and aggregation of these metrics, the Analytic Hierarchy Process (AHP) [3] was used. AHP is a suitable method because it provides a clear, traceable means of eliciting subjective assessments and determining a set of overall weights for a multi-criteria analysis. It is not the only method that possesses these traits, methods such as ELECTRE, TOPISIS and MACBETH also possess these qualities, but AHP is arguably the most well known and widely used [8]. One of its main strengths is that it encourages a hierarchical decomposition of goals which helps ensure that like items are contrasted by Subject Matter Experts.

In order to determine appropriate weighting factors for each of the criteria and sub-criteria, AHP begins with presenting the FOMs to individual subject matter experts (SMEs). The SMEs are asked to provide a pairwise comparison of all FOMs in a hierarchical way. That is to say that all sub-criteria on any single branch of the tree in Figure 2 are compared against each other, but not against sub-criteria from another branch. Similarly, all FOMs at the criteria level are compared to each other.

Individual judgments from the SMEs are collected and using the AHP, a set of weights is produced for the criteria and sub-criteria. A check is also performed to ensure that the individual SME judgments are consistent to within an acceptable level (see Section 3.3.5). If there is strong inconsistency between individual SME judgments, the process allows the SMEs to re-evaluate their responses, identify the reasons for their inconsistency and make corrections as required (Figure 3).

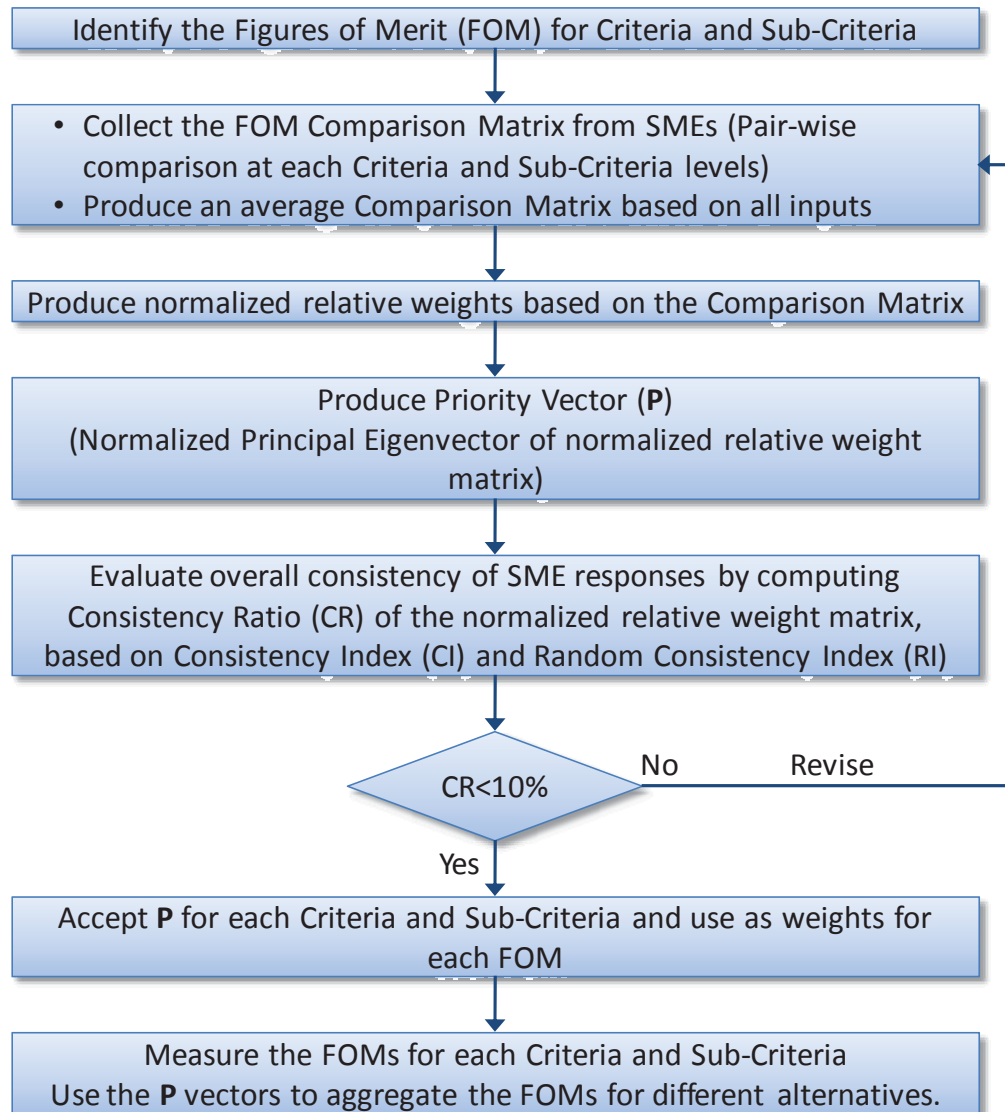


Figure 3 Analytical Hierarchy Process

3.3.3 The comparison matrix

One of the strongest attributes of the AHP is that it uses a pairwise comparison analysis method to identify the priority value or the weight scale of individual measures. Table 1 shows how the Relative Importance of each category is converted into a corresponding numerical score in [3].

Table 1 List of relative importance

Relative Importance	Value
Equal Importance	1
Somewhat important	3
More Important	5
Much more important	7
Extremely more important	9

For each SME, several comparison matrices can be created (one at the criteria level and one for each of the groupings at the sub-criteria level). Table 2 shows a generic example of a comparison matrix for 4 FOMs, where each SME is required to provide values for ξ_1 to ξ_6 based on the values from Table 1. For example, if the SME selects FOM1 as being somewhat more important relative to FOM2, the value for ξ_1 is 3. Similarly, if FOM3 is more important than FOM1, then the value of ξ_2 is $1/5=0.2$.

Table 2 Comparison matrix

	FOM1	FOM2	FOM3	FOM4
FOM ₁	1	ξ_1	ξ_2	ξ_3
FOM ₂	$1/\xi_1$	1	ξ_4	ξ_5
FOM ₃	$1/\xi_2$	$1/\xi_4$	1	ξ_6
FOM ₄	$1/\xi_3$	$1/\xi_5$	$1/\xi_6$	1

Based on all inputs from all SMEs, an average comparison matrix can be produced by calculating the geometric mean of corresponding elements from each SME's individual comparison matrix, as shown in the following equation:

$$a_{avg} = \left(\prod_{k=1}^N a_k \right)^{1/N} \quad (1)$$

where:

- a_k individual matrix element from k^{th} SME,
- a_{avg} geometric mean of each element of matrix, and
- N total number of SMEs.

For example, the value of ξ_1 in the average comparison matrix would be obtained by taking the geometric mean of the N values of ξ_1 from within each of the SMEs' comparison matrices.

3.3.4 Normalized matrix

Normalizing the average comparison matrix can be done based on the ratio of each element of the matrix to the sum of all elements in that column. Table 3 shows the normalized average comparison matrix for the generic 4 FOM comparison matrix shown in Table 2. The μ_i are computed as follows:

$$\begin{aligned}\mu_1 &= 1 + \frac{1}{\xi_1} + \frac{1}{\xi_2} + \frac{1}{\xi_3} \\ \mu_2 &= \xi_1 + 1 + \frac{1}{\xi_4} + \frac{1}{\xi_5} \\ \mu_3 &= \xi_2 + \xi_4 + 1 + \frac{1}{\xi_6} \\ \mu_4 &= \xi_3 + \xi_5 + \xi_6 + 1\end{aligned}\tag{2}$$

Therefore, Table 3 shows the overall normalization matrix of the FOMs.

Table 3 Normalized comparison matrix

	FOM1	FOM2	FOM3	FOM4
FOM ₁	$1/\mu_1$	ξ_1/μ_2	ξ_2/μ_3	ξ_3/μ_4
FOM ₂	$(1/\xi_1)/\mu_1$	$1/\mu_2$	ξ_4/μ_3	ξ_5/μ_4
FOM ₃	$(1/\xi_2)/\mu_1$	$(1/\xi_4)/\mu_2$	$1/\mu_3$	ξ_6/μ_4
FOM ₄	$(1/\xi_3)/\mu_1$	$(1/\xi_5)/\mu_2$	$(1/\xi_6)/\mu_3$	$1/\mu_4$

3.3.5 Weight values and consistency test

The priority vector (P) or normalized principal eigenvector can be calculated based on the normalized average comparison matrix computed in the previous step (such as the one shown in Table 3). Following AHP, the weight for each FOM is the associated element in the normalized principle eigenvector (the eigenvector associated with the largest eigenvalue λ_{\max}) of the normalized average comparison matrix. That is to say:

$$P = \langle w_1, w_2, \dots, w_T \rangle\tag{3}$$

where:

- T total number of FOMs,
- w_j weighting factor for FOM_{*j*}.

The justification for this procedure can be found in [3]. Determining the eigenvector and eigenvalue of a large matrix can be complex and in practice, a specialized commercial software tool (e.g., Matlab) is employed to perform this step. To evaluate the consistency of the average response of all SMEs, the principal (largest) eigenvalue (λ_{max}) is required. To compute the Consistency Index (*CI*), the following equation is used:

$$CI = \frac{\lambda_{max} - M}{M - 1} \quad (4)$$

Where:

- M the size of the comparison matrix.

The next step is to calculate the Consistency Ratio (*CR*), which is dependent on the *CI* and the Random Consistency Index (*RI*). The random consistency index can be selected from Table 4, which shows the results of random consistency index calculations based on a sample size of 500 matrices [3].

Table 4 Random consistency index

M	1	2	3	4	5	6	7	8	9	10
<i>RI</i>	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Therefore, the *CR* is defined as:

$$CR = \frac{CI}{RI} \quad (5)$$

where the consistency conditions are as follows:

- $CR \leq 10\%$ The SME's responses were consistent; therefore, the selected weights can be used in the aggregation step.
- $CR > 10\%$ The SME's responses were not consistent; therefore, the individual SME comparison tables need to be revised.

3.3.6 The AHP aggregation process

Having established weights for the all the evaluation criteria as per equation (3), the process for aggregating the FOMs into an overall measure of system utility is shown in Figure 4. Specifically, the overall utility of an ISR architecture, or Measure of ISR Effectiveness (MOIE), can then be computed using:

$$S = \sum_{i=1}^n w_i s_i \quad (6)$$

where w_i is the requirement-dependent set of weights obtained using AHP as in (3) and s_i represents the values of FOM_{*i*} (the criteria) normalized to the interval [0,1]. Note that the normalized performance s_i explicitly depends on the requirement whereas FOM_{*i*} depends on the requirement for some FOMs (e.g., revisit time) and is independent of the requirement for others (e.g., sensor range). Since the decomposition of FOMs is hierarchical, the process is repeated until the aggregation spans the entire hierarchy:

$$s_i = \sum_{j=1}^m w_{i,j} s_{i,j} \quad (7)$$

$$s_{i,j} = \sum_{k=1}^l w_{i,j,k} s_{i,j,k} \quad (8)$$

Figure 4 shows the FOMs and their associated weights from the criteria and sub-criteria levels. This will aggregate all the FOM data based on their weight scale to produce the overall MOIE.

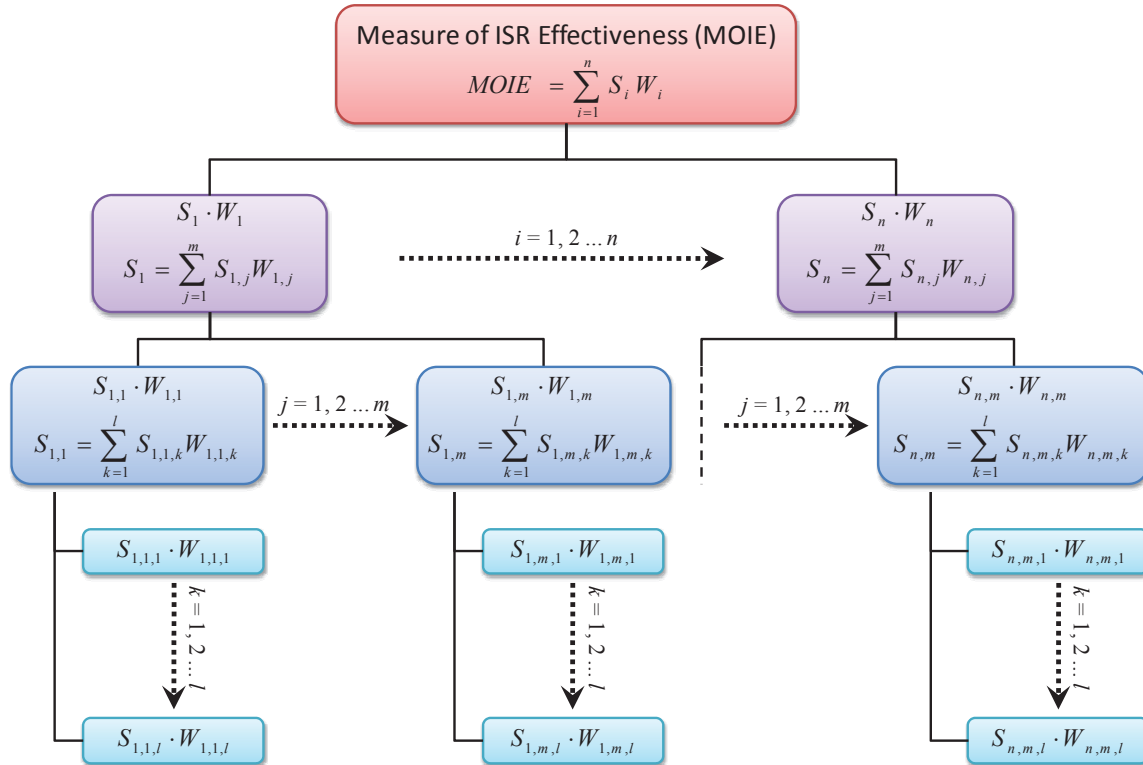


Figure 4 Measure of ISR Effectiveness computation process based on AHP

3.4 ISR systems mission modelling

Military utility assessment will ultimately help address the problem of deciding how to optimize the distribution of platforms and still satisfy mission requirements. This optimization scheme can be based on factors such as cost, sensor coverage or availability. Solving this optimization problem is difficult because it constitutes a large trade space, although the method described earlier in this section can be used to evaluate the many alternatives. The challenge is compounded by the fact that military utility can mean different things to different analysts.

The method described earlier can be used to perform the assessment of military utility. Ideally, this assessment would be supported by data coming from real-world exercises. However, this is prohibitively expensive in general. A more suitable alternative is to therefore use a synthetic environment to model the components of the ISR architecture and thereby obtain the data needed to perform the assessment of military utility. This report will present a sample analysis that shows the steps of this assessment process using SBS as an example.

A generic assessment plan can be formulated for any ISR concept, but the military utility can only be assessed within an analysis framework that clearly defines the mission requirements, the sensor performance parameters and all pertinent aspects of the scenario. The sensors, the performance parameters and platform locations of all of friendly ISR assets must be described throughout the engagement. As shown in Figure 5, different levels of models exist depending on the desired outcome of the system. Each level has models that measure metrics at different levels of aggregation and resolution [9].

For low-level analysis the engineering models typically produce MOPs, mission and engagement models produce Measures of Effectiveness (MOEs), and campaign models produce Measures of Outcome (MOOs). For example, the military utility for a new SBS might be measured at the engineering level by the probability of detection of a certain target class. At the campaign level, the military utility would best be measured by reduced attrition rates over the duration of a conflict.

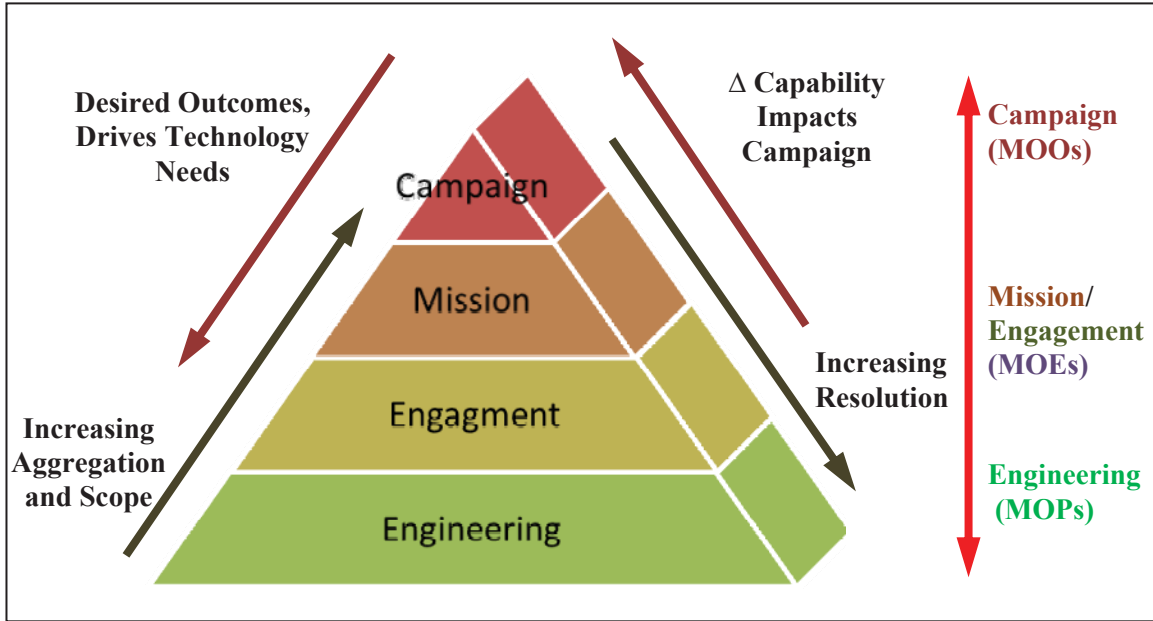


Figure 5 Modelling pyramid

Figure 6 shows the first task in establishing a framework for analysis and the process used to formulate a formal assessment plan for evaluating an ISR system. Several assumptions have been made to better define the scope of this task and ultimately, the assessment of an ISR system must be placed within the context of a full ISR architecture.

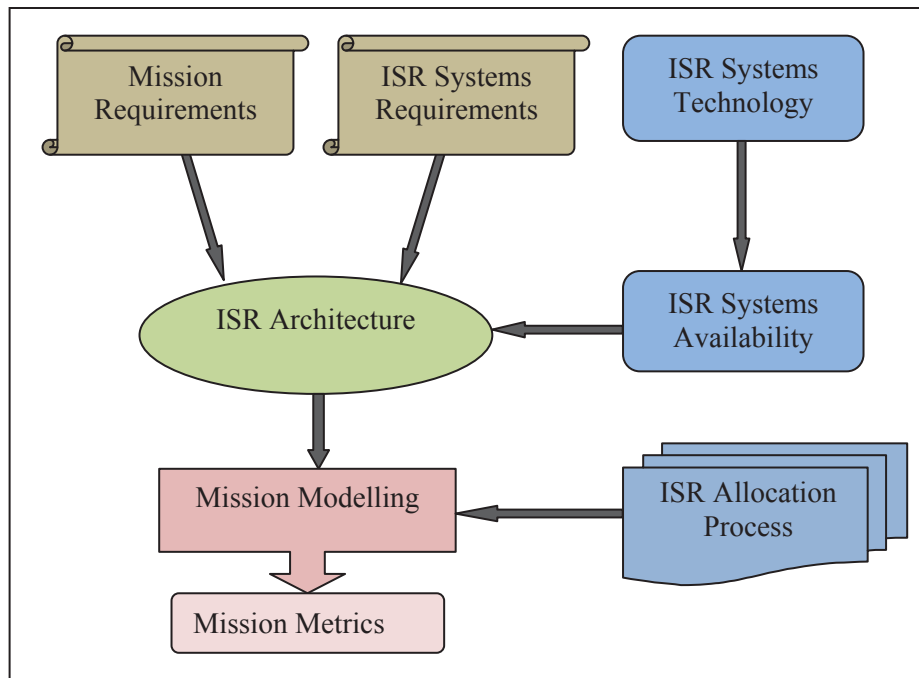


Figure 6 Assessment and modelling schematic

An ISR architecture will be designed based on inputs from:

- Mission Requirements,
- ISR System Requirements, and
- ISR Systems Availability.

The mission modelling will be conducted based on the designed ISR architecture and ISR allocation process. Then, from mission modelling, the mission matrices will be produced for utility assessment of an ISR system.

Many software packages are available for assisting with modelling and simulation of ISR architectures. For example, Defence R&D Canada (DRDC) Ottawa's Simulation Laboratory (SIMLAB) provides a versatile environment in which a wide variety of dynamic systems can be modelled and simulated. The facility can demonstrate the added performance provided by the introduction of new assets into surveillance architecture.

Overall effectiveness of the surveillance architecture, as well as efficiency of existing systems, can be assessed quantitatively. A key feature of SIMLAB and many other modelling and simulation environments is the ability to compare the capability of different surveillance system configurations at the engineering level as shown in Figure 7. Timely detection and tracking of targets is the design objective of new surveillance systems. SIMLAB helps to show how this may be achieved and evaluated.

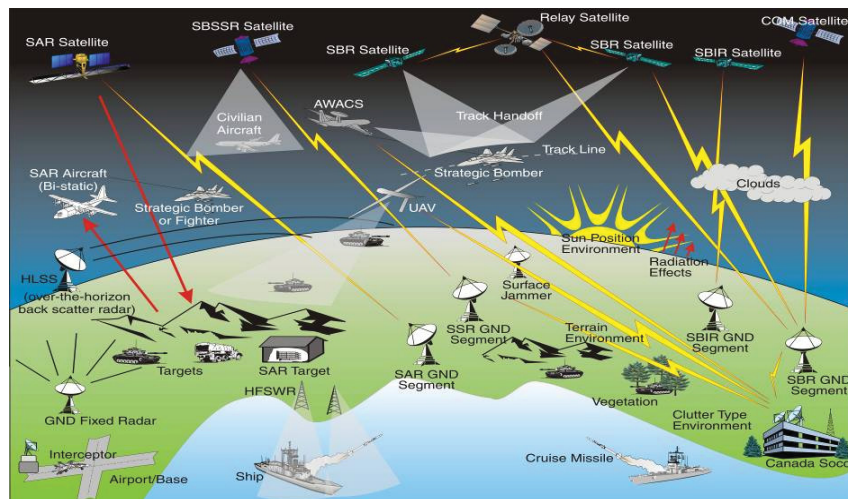


Figure 7 Simulation Laboratory (SIMLAB)

3.5 ISR systems performance evaluation

Here, an example is used to illustrate how to conduct mission performance evaluation of adding new ISR system(s) to existing ISR capability using the evaluation method proposed in this report.

For this example, the SBS is used as the new ISR capability. SBS are an interesting case because their roles have been changing not only due to technological advances, but also due to the complex issues of today's security environment, where an ISR asset is required to support military operations in a matter of hours or even minutes anywhere in the world. The number of operational SBS has been increasing rapidly in the last 30 years, but this increase has also raised a number of issues: increasing amount of man-made debris in space, increasing complexity in space asset management, increasing data handling requirements, etc. All these changes, due to technology advances, increasingly demanding military operational goals, and the high rate of systems development and launch capability, makes an in-depth evaluation and analysis indispensable. Such an evaluation should focus not only on the engineering aspects during development, but also on how these assets can improve the overall defence capability that is required to satisfy current and future ISR goals [2].

3.5.1 Space-based systems

Persistent, non-intrusive, robust and responsive global surveillance capabilities are the ultimate goal of many new ISR developments. One such area of development has been to increase ISR capability from space. SBS provide a number of advantages over ground-based and airborne systems, but also exhibit a number of disadvantages. Both need to be considered and evaluated within the context of an overall ISR architecture and the specific application or concept of operation [2]. Some of the advantages of SBS are deep look, wide area surveillance, and multi-area surveillance capabilities. Some of the drawbacks are high initial cost, complexity and the predictability of their orbits. The high number of current SBS development activities (e.g., the Radarsat-2 project and Radarsat Constellation Mission (RCM) from Canada [10,11], the Tac-Sat program from the United States (US) [12], SAR-Lupe from Germany [13], and the European Helios satellites [14]) suggests that in many cases the benefits outweigh the costs. Additionally, there are a number of new SBS concepts, such as small (e.g., micro and nano sized) satellites, that are being actually pursued. Small satellites refer to satellites with weight less than 500 kilograms, and micro satellites refer to satellites with weight between 10 to 100 kilograms, and nano satellites refer to satellites with weight of 1 to 10 kilograms.

The small satellite concept has been increasingly evaluated as an alternative to traditional large satellites [15] which carry comparatively larger initial costs, limited potential launch platforms, and require dedicated ground segments. Small satellites have their disadvantages, such as higher operating costs. As the number of these types of satellites increases, so do the management, data processing, correlation and dissemination efforts needed to operate them. On other hand, small satellites can provide significant flexibility for operations since they are capable of being launched almost anytime and anywhere. They can also have local command and control centres as well as provide data directly to any user, whether at the strategic, operational or tactical level. These satellites can also have different roles within the same mission, such as serving as a communications node, while also providing for mapping, surveillance, reconnaissance, or battle damage assessment.

The selection of the right SBS concept to achieve the desired goals or requirements has made it challenging for decision makers to decide which concepts best suit their current and future needs. The proposed method, supported by a modelling and simulation, exploitation, and evaluation environment, is designed to assist with these decisions by objectively assessing the strengths and weaknesses of new SBS concepts for military ISR operations.

3.5.2 The scenario

A sample scenario has been used to evaluate the contribution of SBS assets (both as a single asset and as a constellation of different sizes) to the overall surveillance and reconnaissance architecture. For this scenario, a maritime monitoring vignette has been selected with a number of targets moving with different courses and speeds in a coastal area. The mission is to provide situational awareness of the coastal area. Different types of ISR systems have been considered, such as Uninhabited Aerial Vehicles (UAVs), ground-based sensors and space based systems as shown in Figure 8. The UAV and ground-based sensors are considered in this scenario as baseline assets or capability. Different sizes and mixes of ISR systems, including SBS, are considered as alternatives for evaluation of their effectiveness.

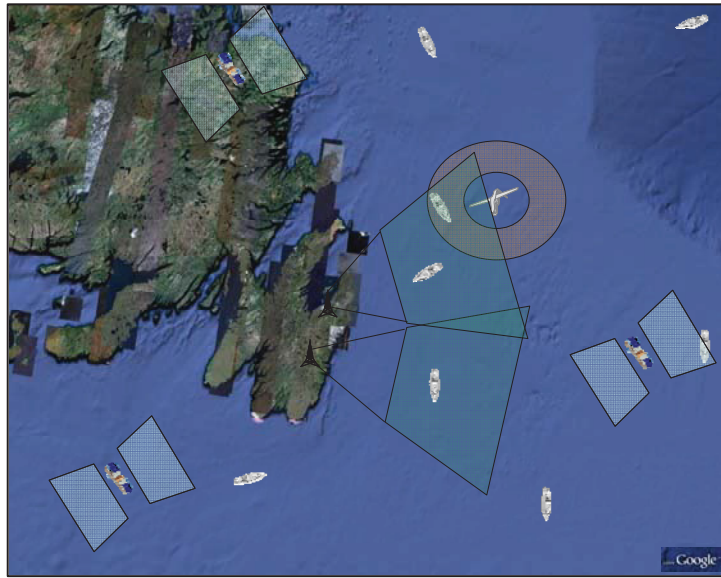


Figure 8 A sample maritime scenario

3.5.3 The evaluation FOM selection

For this example, the Measure of ISR Effectiveness was partially assessed by calculating a set of FOMs that are presented in a hierarchy that reflects the operational requirements for ISR support from a military perspective. The strength of this hierarchy is that it decomposes the ISR requirements into a number of activities, which are associated with higher-level FOMs, and that it organizes subordinate activities, which are likewise associated with lower-level FOMs. In this way, the hierarchy allows the lower-level activities to be assessed using objective MOPs (i.e., the lower-level FOMs) and introduces the systematic aggregation of these measures up to the highest level (i.e., the MOIE), which represents an assessment of the architecture's military utility, as shown in Figure 2.

3.5.3.1 Figures of merit – high-level ISR objectives (goal)

To illustrate how a high-level FOM can be derived for this example, this report takes the Sensor-to-Shooter concept as an example. The concept of sensor-to-shooter (Figure 9) in the military captures the sequence of actions that need to be taken in order for the military to move from sensing a target to acting on a target. These actions are: Find, Fix, Track, Target, Engage, and Assess and are collectively known as the Sensor-to-Shooter Cycle [16].

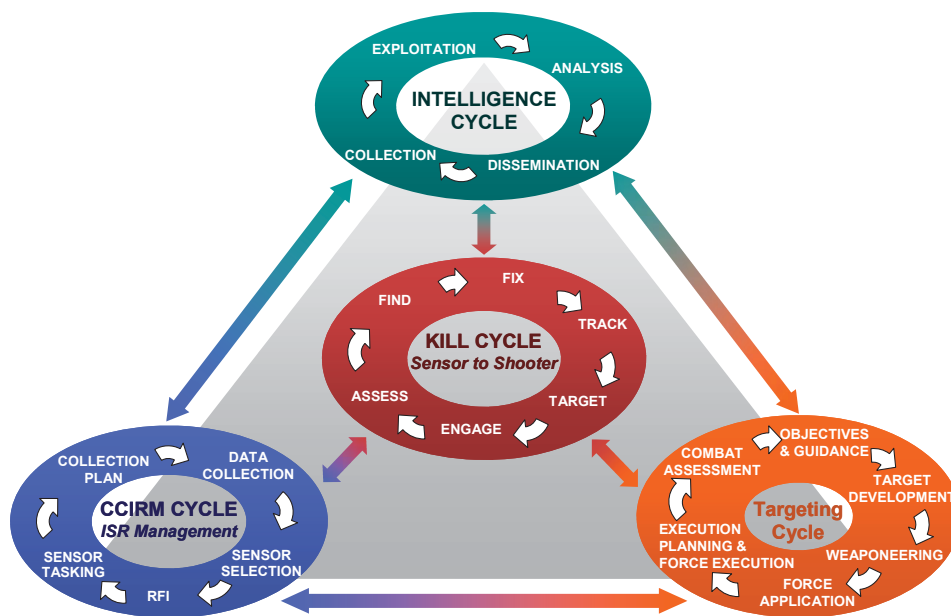


Figure 9 Expanded Sensor-to-Shooter concept

Figure 9 shows the Sensor-to-Shooter concept as integrated with the Intelligence Cycle, the Targeting Cycle, and the Collection, Coordination and Intelligence Requirements Management (CCIRM) Cycle. Intelligence (cycle) refers to the ability of an ISR system to locate, surveil, distinguish and track moving objects, while Targeting refers to the capability of generating the desired effects and performing assessment of the results. Finally, the ISR Management Cycle refers to the tasking, collection and dissemination of surveillance products. In this report, the effectiveness of an ISR architecture is assessed in the context of its ability to perform the various ISR activities within the Sensor-to-Shooter Cycle.

3.5.3.2 Figures of merit – ISR activities (criteria)

From the Sensor-to-Shooter Cycle, it is possible to decompose the Intelligence and the Targeting support functions into key ISR activities, which form the next level of FOMs. In this example, three activities related to the Intelligence support process are presented to illustrate the next level of FOMs (Table 5).

Table 5 Figures of merits - ISR activities (criteria)

Figure of merit	Name	Description
Criterion-1	Tasking	The tasking procedure is used to direct and prioritize collection requirements, and form the interface between consumers and producers of intelligence products.
Criterion-2	Detection	Sensors are required to be available and capable of detecting high-velocity threat projectiles, over a range sufficient to provide early warning and with enough precision to enable targeting processes to engage the target.
Criterion-3	Tracking	The ISR architecture should have the potential to provide capabilities for rapidly detecting, precisely locating, and accurately classifying fixed and moving threats from standoff distances, in order to track threats. Multi-platform/multi-sensor tracking with data fusion techniques can be used. Taking into consideration various countermeasures, capabilities such as these could be achieved by designing, performing and assessing advanced tracking algorithms.

3.5.3.3 Figures of merit – quantitative measures of performance (sub-criteria)

From each ISR activity, the next level of the hierarchy is formed using several quantitative measures of performance, which make up the sub-criteria FOMs. At this level, the measures of performance quantify a specific characteristic or behaviour of the ISR architecture. They can be defined as “the quantitative indicators of the performance capabilities of a system” [5], where “performance” is considered the quality of the process the system uses to achieve its purpose. The following FOMs are used to illustrate how an ISR activity might be decomposed into several lower-level FOMs (Table 6).

Table 6 Figures of merits: quantitative measures of performance (sub-criteria)

Figure of merit	Name	Description
Sub-Criterion-1.1	Response Time	Response time is the average time elapsed after receiving a request to observe any selected region and perform an assigned mission, and getting the initial product back to the requester. From a systems and operations perspective, it is a sub-measure that measures the overall responsiveness of an ISR architecture.
Sub-Criterion-1.2	Number of Revisits	Number of revisits is the frequency with which a particular region is visited and searched by the ISR sensors. This sub-measure is an important specification of any ISR architecture.
Sub-Criterion-1.3	Gap/Revisit Time	The duration of gaps in the coverage of an area of interest (AOI) will determine the time interval to revisit the AOI. Such gaps are due to the available sensors that scan a particular AOI. Within the criteria FOM sensor-to-shooter, shortening the coverage gap time is important, especially in the Find, Fix, Track and Assess phases. Not only will a longer coverage gap time degrade the degree of success of the Sensor-to-Shooter Cycle, it will also increase the threat posed by targets that were not detected due to sensor vacancies over the area of conflict.
Sub-Criterion-1.4	Coverage (Search Percentage)	Coverage search percentage is the percentage of time spent searching during the entire scenario and shows how efficiently an ISR system performs in terms of searching a desired region within a certain period of time. This value will influence the detection and tracking performance of the ISR architecture.
Sub-Criterion-2.1	Overall Number of Detections	The number of detections performed by the ISR architecture can affect the sensor-to-shooter success due to the increasing possibility of initiation and maintaining of tracks on hostile targets.
Sub-Criterion-2.2	Detection Gap Time (DGT)	Gaps between detections degrade the performance of the ISR architecture, which in turn affects the Sensor-to-Shooter Cycle. Gap time will affect track initiation and track life time.

Sub-Criterion-2.3	Probability of Detection (Pd)	Pd is the ratio of detected targets with respect to the number of times the sensor had opportunity to detect the target. Pd computation is mainly based on signal-to-noise ratio for radar systems. As the signal-to-noise ratio increases, the Pd value will increase as well.
Sub-Criterion-3.1	Track Initiation	The track phase in the Sensor-to-Shooter Cycle is a function of a set of factors. One of these factors is how early a track can be initiated. Reducing the response time and increasing sensor availability will in turn increase the probability of having earlier detections on targets. This leads to a higher possibility of track initiation at an earlier time.
Sub-Criterion-3.2	Average Track Lifetime	Average Track Lifetime is obtained by dividing the Total Tracking Time by the number of tracks initiated. An ideal ISR architecture will be required to maximize the track lifetime for classification and targeting. The track lifetime is based on the availability of ISR sensor coverage of an AOI and the priority of tracked targets.
Sub-Criterion-3.3	Number of Tracks	The number of targets that can be tracked by an individual sensor or group of sensors

3.5.4 The comparison matrices

Once the hierarchy is established, comparison matrices can be created based on criteria and sub-criteria levels, as shown previously in Tables 5 and 6. For the purpose of this work three SMEs were consulted for the evaluation and their combined results are shown in Tables 7 and 8. Note that there are sub-criteria for only three of the six criteria: Tasking, Detection and Tracking. The data was not available for the rest of the criteria at the time of writing and the authors felt that the available data would be sufficient for a proof of concept and to illustrate the main ideas.

Table 7 Comparison results for criteria level

	Tasking	Detection	Tracking	Processing	Exploitation	Dissemination
Tasking	1.000	0.794	1.000	0.481	0.693	0.693
Detection	1.260	1.000	1.518	0.794	1.442	0.874
Tracking	0.659	1.000	1.000	0.693	0.550	1.000
Processing	2.080	1.260	1.442	1.000	1.518	2.080
Exploitation	1.442	0.693	1.817	0.659	1.000	1.442
Dissemination	1.442	1.145	1.000	0.481	0.693	1.000

Table 8 Comparison results for sub-criteria level

	Response	Revisit	Coverage	# of Detection	Detection Gaps	Pd	Track Initiation	Track Life	# of Tracks
Response	1.000	0.362	0.281						
Revisit	2.759	1.000	1.063						
Coverage	3.557	0.941	1.000						
# of Detection				1.000	2.027	0.322			
Detection gaps				0.493	1.000	0.523			
Pd				3.107	1.913	1.000			
Track Initiation							1.000	0.405	0.493
Track Life							2.466	1.000	0.794
# of Tracks							2.027	1.260	1.000

The normalized tables for the criteria (Table 9) and sub-criteria (Table 10) are produced based on the methodology shown in Sub-section 3.3.4 and the data from Tables 7 and 8. The priority vector for each criterion and sub-criterion was computed based on the method presented in Section 3.4 and the results are shown in Tables 9 and 10.

Table 9 Normalized comparison matrix for criteria level

	Tasking	Detection	Tracking	Processing	Exploitation	Dissemination	Priority Vector
Tasking	0.127	0.135	0.129	0.117	0.118	0.098	0.120
Detection	0.160	0.170	0.195	0.193	0.245	0.123	0.181
Tracking	0.084	0.170	0.129	0.169	0.093	0.141	0.131
Processing	0.264	0.214	0.185	0.243	0.257	0.293	0.243
Exploitation	0.183	0.118	0.234	0.160	0.170	0.203	0.178
Dissemination	0.183	0.194	0.129	0.117	0.118	0.141	0.147

Table 10 Normalized comparison matrix for sub-criteria level

	Response	Revisit	Coverage	# of Detection	Detection Gaps	Pd	Track Initiation	Track Life	# of Tracks	Priority Vector
Response	0.137	0.157	0.120							0.138
Revisit	0.377	0.434	0.453							0.422
Coverage	0.486	0.409	0.427							0.440
# of Detection				0.217	0.410	0.174				0.267
Detection gaps				0.107	0.202	0.283				0.198
Pd				0.675	0.387	0.542				0.535
Track Initiation							0.182	0.152	0.216	0.183
Track Life							0.449	0.375	0.347	0.390
# of Tracks							0.369	0.473	0.437	0.426

The λ , CI , RI and CR were calculated based on both Tables 9 and 10 and the results are shown in Table 11. Based on results shown in Table 11, the criteria and sub-criteria weights selected were consistent. Therefore, these weights can be used for evaluation of the different ISR configurations.

Table 11 Weight selection consistency results

	λ	n	CI	RI	CR (%)	<10%	Description
Criterion: Intelligence Cycle	6.12	6	.024	1.24	2	Yes	Consistent
Sub-Criterion: Coverage	3.01	3	.005	.58	1	Yes	Consistent
Sub-criterion: Detection	3.08	3	.04	.58	7	Yes	Consistent
Sub-criterion: Tracking	3.02	3	.01	.58	2	Yes	Consistent

3.5.5 FOM measurement and aggregation of results

There are nine alternatives (different SBS constellation sizes and type configuration mixes) that were considered for the evaluation:

- Baseline ISR capability
- Baseline ISR capability and n SBS, where $n=1, 2, 12, 24, 27, 30, 36, 48$.

The first alternative was based on baseline capability, which includes a single UAV with two coastal radars. The remaining alternatives were formed by adding SBS assets to the baseline in order to evaluate the improvement in performance that might result. Table 12 shows the measures that were collected from simulation of the scenario, which were normalized with respect to the best value achieved by any of the configurations. Table 13 shows the aggregation results for first three criteria and their sub-criteria based on the methodology shown in Section 3.3.6 and Figure 4.

Table 12. List of sub-criteria FOMs and their scores and weights

FOM		Baseline	Baseline + 1 SBS	Baseline + 2 SBS	Baseline + 12 SBS	Baseline + 24 SBS	Baseline + 27 SBS	Baseline + 30 SBS	Baseline + 36 SBS	Baseline + 48 SBS	Weights
Criteria	Sub-Criteria										
Task											
	Response	0.065	0.065	0.065	0.088	0.151	0.771	0.780	0.889	1.000	0.138
	Revisit	0.001	0.002	0.002	0.003	0.006	0.771	0.780	0.889	1.000	0.422
	Coverage	0.233	0.247	0.254	0.319	0.453	0.988	0.990	0.991	1.000	0.440
Detect											
	# of Detection	0.162	0.165	0.178	0.251	0.456	0.833	0.833	0.905	1.000	0.267
	Detection gaps	0.019	0.025	0.030	0.051	0.187	0.179	0.179	0.276	1.000	0.198
	Pd	0.233	0.247	0.254	0.319	0.453	0.988	0.990	0.991	1.000	0.535
Track											
	Track Initiation	0.001	0.004	0.004	0.006	0.024	0.179	0.179	0.276	1.000	0.183
	Track Life	0.017	0.087	0.087	0.123	0.224	0.833	0.833	0.905	1.000	0.390
	# of Tracks	0.093	0.123	0.123	0.174	0.316	0.833	0.833	0.905	1.000	0.426

Table 13. List of criteria FOMs, their scores and weights, and MOIE results

Criteria	Baseline	Baseline + 1 SBS	Baseline + 2 SBS	Baseline + 12 SBS	Baseline + 24 SBS	Baseline + 27 SBS	Baseline + 30 SBS	Baseline + 36 SBS	Baseline + 48 SBS	Weights
Task	0.112	0.119	0.122	0.154	0.223	0.867	0.873	0.934	1.000	0.120
Detect	0.172	0.181	0.189	0.248	0.401	0.787	0.788	0.827	1.000	0.181
Track	0.046	0.087	0.087	0.123	0.226	0.713	0.713	0.789	1.000	0.131
MOIE	0.051	0.059	0.060	0.079	0.129	0.340	0.341	0.365	0.432	

Figure 10 shows the overall criteria level performance by each ISR configuration mix. As the results show, the detection criterion has higher performance values, based on the results of the SMEs' opinions. Also, there is a significant performance increase as the number of SBS increases from 2 to 27, and a much lower increase in performance when the number of SBS is increased from 0 to 2 and from 27 to 48.

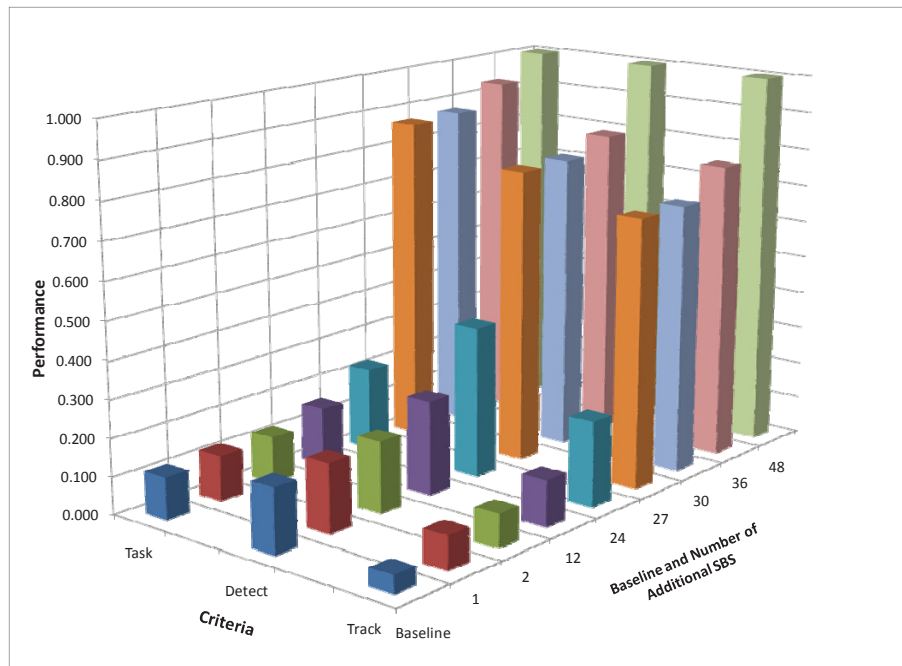


Figure 10 Criteria results

Figure 11 shows the MOIE results for each alternative and the “sweet spot” region where the number of SBS has most significant impact on overall performance. Not surprisingly, the MOIE behaviour is similar to the behaviour of the criteria shown in the same as the results of criteria behaviour as shown in Figure 10. The sweet spot can be shifted to left or right and also can have different slope based on the weights obtained using SME judgment. The figure also shows how varying numbers and combinations of SBS can have different impacts on different missions. By emphasizing the sensitivity with respect to different missions, the number and mix of SBS can be designed to address the specific requirements across multiple missions.

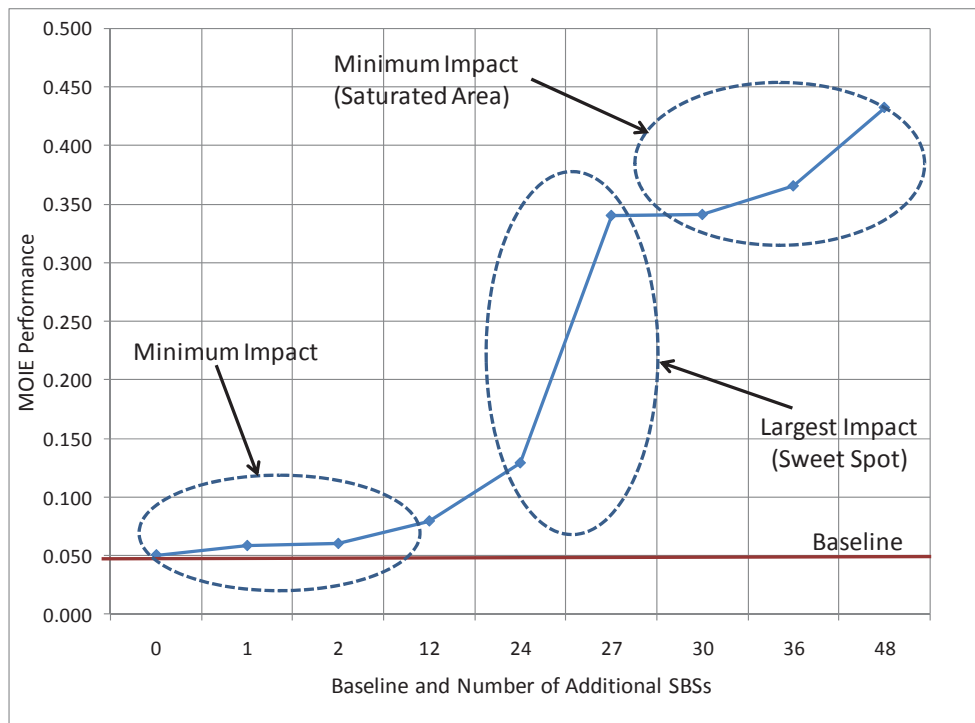


Figure 11 MOIE results

4 Conclusion

This report proposed and described in detail a method to analyze and evaluate the effectiveness of different ISR architectures using a hierarchy of Figures of Merit (FOMs) that are aggregated up the framework to provide a Measure of ISR Effectiveness (MOIE). Furthermore, this report evaluated select lower-level FOMs as evidence of how an augmented architecture can achieve military goals and overcome some of the significant limitations exhibited by individual ISR assets. This report also proposes selected sets of FOMs, which were used to evaluate the effectiveness of the different ISR architectures. The integrated ISR architectures seen in this report are more effective at detection and tracking of targets than current stand alone systems. Both the baseline sensors and the additional sensors help to offset the disadvantages of each other, while creating a robust surveillance system architecture that provides an enhanced strategic and tactical capability for military operations. Therefore, the augmented architecture is well suited to combat emerging threats. Ultimately, questions about which configuration is best-suited to a particular set of missions may require additional analysis. When combined with system costs, the MOIE can be used as the basis of a cost-benefit analysis whose goal is to identify which solutions should form the cornerstone of any future ISR architecture.

Given the increasing complexity of SBS, it is important to use a traceable, repeatable, and robust method to assess how a proposed constellation of SBS will contribute to military ISR missions. The method presented in this report was able to accomplish this task. Using a hierarchical decomposition of the high-level goals allows for a systematic consideration of the factors that make for desirable SBS performance. While used for SBS in this report, the method can easily be generalized to other military and civilian scenarios.

Future work to expand on the method described in this report could focus on dealing with the potential inter-relations between FOMs. For example, there is currently nothing to prevent someone from naively including both the revisit time of an ISR asset and the frequency of updates it provides as distinct FOMs in a hierarchy of ISR metrics, even though there is a clear link between the two. An investigation of several common FOMs could help refine the current approach using a method such as the Analytical Network Process as a basis, rather than the AHP-based formulation this report describes..

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List of symbols/abbreviations/acronyms/initialisms

AHP	Analytical Hierarchy Process
AMDGT	Average Maximum Detection Gap Time
C2ISR	Command, Control, Intelligence, Surveillance and Reconnaissance
C4ISR	Command, Control, Communications, Computers, Intelligence Surveillance and Reconnaissance
CCIRM	Collection, Coordination and Intelligence Requirements Management
<i>CI</i>	Consistency Index
<i>CR</i>	Consistency Ratio
DGT	Detection Gap Time
DND	Department of National Defence
DRDC	Defence R&D Canada
DRDKIM	Director Research and Development Knowledge and Information Management
DTED	Digital Terrain Elevation Data
GIS	Global Positioning System
FOM	Figures of Merit
EO	Electro-Optical
IR	Infrared
ISR	Intelligence Surveillance and Reconnaissance
MCA	Multi-Criteria Analysis
MOIE	Measure of ISR Effectiveness
MOE	Measure of Effectiveness
MOO	Measure of Outcome
MOP	Measure of Performance
MSI	Multi-Spectral Imagery
Pd	Probability of Detection
<i>P</i>	Priority Vector
R&D	Research and Development
RCM	Radarsat Constellation Mission
<i>RI</i>	Random Consistency Index
SAR	Synthetic Aperture Radar

SBR	Space Based Radar
SBS	Space Based Surveillance
SIMLAB	Simulation Laboratory
SME	Subject Matter Expert
SMTI	Surface Moving Target Indication
T	Total Number of FOMs
UAV	Uninhabited Aerial Vehicle
US	United States
w_j	Weighting Factor for FOMs
λ_{\max}	Principal Eigenvalue

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Intelligence, Surveillance and Reconnaissance (ISR) systems form the backbone of any military defence and security operation. These systems, be they ground-, sea-, air- or space-based, do so by providing enhanced situational awareness to the military decision makers at the tactical, operational and strategic levels. Whereas traditional surveillance systems operate within one environment and at one level, current military requirements and technological advances have evolved to multi-domain, multi-level sensor systems. For example, Space-Based System (SBS) technology has been advancing rapidly in terms of capability, affordability, size and reliability. As in the commercial sector, defence and military institutions are looking to improve their space capabilities by increasing the number of smaller, more affordable and more capable satellites that are being put into service. Given the complexity this introduces, one of the current challenges in this area is to objectively evaluate the effectiveness of a given collection of surveillance systems (i.e., ISR architecture) to the military decision maker. This effectiveness can only be assessed by taking into account a multitude of factors – from geospatial and temporal to information and fusion, all of which combine to describe the military utility of a given architecture. This report presents an end-to-end method for assessing the utility of different ISR architectures from engineering-level simulation and modelling to the evaluation of military Figures of Merit/Measures of Effectiveness. As a proof of concept, a maritime domain awareness scenario is used in this report to evaluate the improved effectiveness of surveillance capability by the addition of an SBS to a current available ISR architecture.

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AHP, MOPs, MOEs, Evaluation, ISR

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