

Viability assessment report on TTRDP GMTI constellation study

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Abstract

Driven by the potential military utility of a satellite constellation providing wide-area space based surveillance, the Trilateral Technology Research and Development Program (TTRDP) envisaged a framework that supports constellation concept design, assessment modeling and system feasibility studies. The concept design's "study and evolve" approach was institutionalized by formulating various teams, each oriented towards distinct research activity, to cooperatively feed on each others inferences.

The performance assessment activity kicked-off with an initial set of constellation design parameters with 36 satellites distributed in 12 orbital planes inclined at 85° . The outcome of iterative research and assessment activities revealed that 27 satellites distributed in nine orbital planes at 63.4° inclination produces equally acceptable results over most of the globe. This report is the result of an effort to deduce the viability of various design trade-offs that the two sets of satellite orbital parameters and constellation patterns can render on the Measure of Performance (MOP).

Simulation Laboratory (SimLab), a simulator built in-house at DRDC Ottawa, and Satellite Tool Kit (STK), a Commercial Off-The-Shelf (COTS) tool, were used as performance modelling and assessment tools to obtain the MOP and statistically evaluate the two constellation patterns. The assessment presented in this report quantifies the MOP based on coverage, detection and tracking analysis, which SimLab exercised on a representative Area of Interest (AOI) and STK on a global scale.

With most of the satellite and sensor's parameters being held constant, a comparative performance validation was conducted against both constellation patterns. Furthermore, by varying the Right Ascension of Ascending Node (RAAN) and phasing angle, a comparative performance validation was also conducted for 27 satellite constellations. The objective of this evaluation assessment is to reveal the combination of constellation sets that produce an acceptable performance at a reduced cost.

Résumé

Mené par l'utilité militaire potentielle d'une constellation de satellites de surveillance de zones étendues, le programme TTRDP (programme trilatéral de recherche et développement en technologie, *Trilateral Technology Research and Development Program*) a prévu un cadre qui permet la conception et l'évaluation par modélisation de constellations ainsi que l'étude de la faisabilité des systèmes. L'approche «d'étude et d'amélioration» du concept et d'élaboration a été formalisée par la création de différentes équipes, chacune chargée d'activités de recherche distinctes, quoique détaillées, et sur la coopération entre chacune d'elles.

L'activité d'évaluation du rendement a débuté par la détermination d'une ensemble initial de paramètres de conception de constellations, soit 36 satellites répartis sur 12 plans orbitaux inclinés à 85°. Les activités de recherche itérative et d'évaluation ont révélé que 27 satellites, répartis sur neuf plans orbitaux d'une inclinaison de 63,4° produiraient des résultats tout aussi acceptables sur la plus grande partie du globe. Le présent rapport est le résultat d'un effort d'interprétation visant à déduire la viabilité des divers compromis de conception que les deux séries de paramètres orbitaux et de configurations de constellations peuvent apporter à la mesure du rendement (MDR) du concept.

Pour les deux configurations de constellations, le SimLab (laboratoire de simulation), un simulateur mis au point à l'interne à RDDC Ottawa, et la STK (boîte à outils logiciels pour satellites, *Satellite Tool Kit*), un progiciel commercial, ont été utilisés comme outils d'évaluation et de modélisation du rendement pour obtenir une MDR et une évaluation statistique. L'évaluation présentée dans ce rapport quantifie la MDR d'après l'analyse de la couverture, de la détection et de la poursuite effectuée au moyen du SimLab, pour une zone d'intérêt (ZI) représentative, et avec la STK à l'échelle planétaire.

En maintenant constants la plupart des paramètres des satellites et des capteurs, une validation comparative du rendement a été menée pour les deux configurations de constellations. De plus, en variant la distribution de l'ADNA (ascension droite du nœud ascendant) et l'angle de phase, on a effectué aussi une validation comparative du rendement pour des constellations de 27 satellites. L'objectif de cette évaluation est de trouver la combinaison de paramètres de constellation qui donne un rendement acceptable, à un coût moindre.

Executive summary

The need for supplementing the existing Intelligence, Surveillance and Reconnaissance (ISR) infrastructure in conjunction with the advent of rapid technological advances has generated significant interest in Canada (CA), the United States (US) and the United Kingdom (UK). These countries are collaborating under TTRDP to investigate and determine the utility of space-based surveillance systems. Feasible sets of constellation configurations and sensor design parameters were the outcome of iterative research activity. The performance assessment, as a follow-up activity, validates the effectiveness and viability of these parameters at the engineering level.

As a starting point for the research activity, an initial constellation of 36 satellites in 12 orbital planes at four slots of phasing angular measure between satellites in adjacent planes was chosen. In order to reduce the size and hence the cost, 27 satellites in nine orbital planes, at lower inclination was proposed as a viable alternative. The stages that were involved in working towards and arriving at the performance assessment facts and figures were:

- Identifying the object of evaluation;
 - The constellation 36/12/4 and 27/9/# are primarily the two objects of evaluation; the *pros and cons* of adopting either are weighed as a function of coverage versus cost. All possible phasing angles for a 27 satellite constellation are exercised on a global scale and the ones that produce best MOPs are chosen for in-depth performance analysis on an Area of Interest (AOI).
 - Between 36/12/4 and 27/9/#, the constellation and orbital parameters such as RAAN spread, phasing angle, inclination and altitude are varied to generate mutations of test cases. The RAAN spread and phasing angle are the design variables that determine the coverage distribution and uniformity respectively, within a given constellation.
- Capturing the evaluation objectives;
 - MOP metrics such as, coverage, revisit and response time at every 5^0 resolution are evaluated to measure the surveillance effectiveness of these constellation configurations on a global scale;
 - MOP metrics such as, detection and tracking assessed against the backdrop of an AOI with 215 Ground Moving Target Indicator (GMTI) targets, is evaluated to measure the effectiveness of constellation configuration and sensor performance.
- Identifying the tools needed to model and simulate the constellation scenario;
 - Satellite Tool Kit (STK) is used to assess the global coverage performance of different constellation configurations;

- Simulation Laboratory (SimLab) is used to assess the constellation and sensor performance on an AOI.
- Statistical comparison and data representation.

The assessment activity conducted at the engineering level, on 36/12/4 and 27/9/# constellations identified several design trade-offs. These findings are summarized as follows:

- Phasing evaluation conducted on the 27/9/# constellation configuration at 180° RAAN spread, showed phasing 3 with maximum coverage, least revisit interval and response time. A similar evaluation conducted on 27/9/# constellation, at 360° RAAN spread, proved phasing 5 constellation the most effective and even better compared to the proposed phasing 3 configuration. This prompted further investigation leading to in-depth performance assessment of 27/9/5 constellation.
- Even though the 36/12/4 constellation exhibited exceptional global coverage performance, 27/9/5 at 360° RAAN produces improved total coverage time with comparably minimum revisit interval and response time, with considerable gaps at the poles. However, the 25% reduction in constellation size and hence the cost, far outweighs the polar gaps.
- Besides orbital and constellation parameters, detection and tracking data largely depend on the duration of sensor Field of View (FOV) over a given AOI. At the chosen epoch time, i.e. 1st April 2010 09:30, the 27/9/3 constellation at 360° RAAN spread, attempted maximum number of detections. The increased detection attempts resulted in an increase in the number of detection success and the total number of track initiations, thus reducing the total detection and tracks gaps.

This report concludes with a list of recommendations, which would enhance constellation design and assessment credentials.

Jassemi-Zargani, R.; Rao, G. 2004. Viability assessment report on TTRDP GMTI constellation study. DRDC Ottawa TM 2004-223, Defence R&D Canada - Ottawa.

Sommaire

La nécessité d'enrichir l'infrastructure existante de renseignement, surveillance et reconnaissance (RSR) en conjonction avec les progrès technologiques rapides ont suscité un intérêt important au Canada, aux États-Unis et au Royaume-Uni. Ces pays collaborent dans le cadre du TTRDP pour étudier l'efficacité des systèmes de surveillance depuis l'espace. Des activités de recherches itératives ont généré des ensembles possibles de paramètres pour les configurations de constellations et la conception des capteurs. L'évaluation du rendement, comme activité de suivi, valide l'efficacité et la viabilité de ces paramètres au niveau technique.

Comme point de départ de l'activité de recherche, une constellation initiale de 36 satellites sur 12 plans orbitaux avec quatre intervalles d'angle de phase entre les satellites sur des plans adjacents a été choisie. Afin de réduire l'ampleur, et par conséquent les coûts, on a plutôt proposé comme solution de rechange viable, le déploiement de 27 satellites sur 9 plans orbitaux de moindre inclinaison. Voici les étapes réalisées pour arriver aux chiffres et aux conclusions de l'évaluation du rendement :

- Identifier l'objet de l'évaluation :
 - Les constellations 36/12/4 et 27/9/# sont les deux principaux objets de l'évaluation; les *avantages et les inconvénients* d'opter pour l'une ou l'autre sont évalués en fonction de la couverture par rapport aux coûts. Tous les angles de phase possibles pour une constellation de 27 satellites sont examinés à l'échelle planétaire et ceux fournissant les meilleures MDR sont soumis à une analyse poussée du rendement dans une zone d'intérêt (ZI).
 - Entre les constellations 36/12/4 et 27/9/#, on a varié des paramètres des orbites et de la constellation comme la distribution de l'ascension droite du nœud ascendant (ADNA), l'angle de phase, l'inclinaison et l'altitude, afin de produire des variantes. La distribution de l'ADNA et l'angle de phase sont les variables de conception déterminant respectivement la distribution et l'uniformité de la couverture d'une constellation donnée.
- Saisir les objectifs de l'évaluation :
 - Des mesures quantitatives du rendement comme la couverture, l'intervalle de survol et le temps de réponse pour chaque intervalle de résolution de 5° en sont évaluées pour mesurer l'efficacité de ces configurations de constellations pour la surveillance à l'échelle planétaire.
 - Des mesures quantitatives du rendement comme la détection et la poursuite sont évaluées sur une ZI criblée de 215 indicateurs de cibles terrestres mobiles (ICTM) pour déterminer l'efficacité des configurations de constellations et le rendement des capteurs.

- Identifier les outils nécessaires pour modéliser et simuler les variantes des constellations :
 - La STK (boîte à outils logiciels pour satellites) est utilisée pour évaluer la couverture de la planète par les différentes configurations de constellations.
 - Le SimLab (laboratoire de simulation) est utilisé pour évaluer la constellation et le rendement des capteurs sur une ZI.
- Comparaison statistique et représentation des données.

Les activités d'évaluation technique des constellations 36/12/4 et 27/9/# ont permis plusieurs compromis de conception. Cette rétroaction et les résultats sont résumés ci-après:

- L'évaluation des phases menée pour la configuration des constellations 27/9/# avec une distribution d'ADNA de 180° montrait que la distribution 3 des phases offrait une couverture maximale avec un intervalle de survol et un temps de réponse moindres. Une évaluation similaire effectuée pour les constellations 27/9/#, avec une distribution d'ADNA de 360° a révélé que la distribution 5 des phases était la plus efficace et même meilleure que la configuration proposée de la distribution 3 des phases. Cela a entraîné une autre étude qui a mené à une évaluation poussée du rendement de la constellation 27/9/5.
- Même si la constellation 36/12/4 offrait une couverture exceptionnelle de la planète, la constellation 27/9/5 avec une distribution d'ADNA de 360° offre une couverture globale améliorée, avec un intervalle de survol et un temps de réponse minimaux comparables. La réduction de 25 % de l'effectif de la constellation, et par conséquent de son coût, compense largement la couverture imparfaite des pôles.
- En plus des paramètres des orbites et des constellations, la détection et la poursuite dépendent en grande partie de la durée pendant laquelle le capteur observe une ZI donnée. Au moment choisi, le 1^{er} avril 2010 à 09 h 30, on a simulé avec la constellation 27/9/3 à une distribution d'ADNA de 360°, la détection d'un nombre maximal de cibles. Un nombre accru de tentatives de détection a produit un plus grand nombre de détections réussies et un nombre total d'amorces de routes qui, dans l'ensemble, ont permis de réduire le nombre total des lacunes pour la détection et pour les routes.

Le présent rapport se termine par une liste de recommandations dont la mise en œuvre, améliorerait la crédibilité en matière de conception et d'évaluation de constellations.

Jassemi-Zargani, R.; Rao, G. 2004. Viability assessment report on TTRDP GMTI constellation study. DRDC Ottawa TM2004-223, R & D pour la défense Canada - Ottawa

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1. Introduction

The prospects of a military employing space for continuous wide-area surveillance combined with on-going technological advances that provide reliable, cost-effective and highly responsive sensor and platforms has pushed the frontiers of space from surveillance to a viable reality.

Over the past decades, the ISR infrastructure showcased only ground based and airborne sensors, with limited use of space based sensors. The utility of such ground and airborne sensors and platforms is valuable for its low cost swift deployment combined with strong signal reception capability at a relatively low transmission power. However, these benefits suffer several shortcomings when faced with operational requirements to provide global coverage, long operating range and complete obscurity during threats. Also, the enormous support structure needed during military missions and mounting operational and maintenance costs contribute to serious drawbacks when existing ISR technologies were adopted for any major global operation.

In the search for alternatives that address these issues and provide long-term solution to the current and futuristic ISR goals, space-based platforms were clearly identified as an option consistent with the requirements. TTRDP was thus established by Canada (CA), the United Kingdom (UK) and the United States (US) to step-up initiatives to investigate the effectiveness and reliability of space based radar.

At its inception, TTRDP was driven by its ambitious plan to provide the ultimate futuristic ISR infrastructure. A large constellation of sophisticated surveillance satellites was conceived to completely replace existing ground based and airborne surveillance assets. However, such efforts ceased due to the high cost and risk involved in conceptually designing and building such an expensive ISR system, at the expense of existing ones that have been tried, tested and proven over the decades.

Alternatively, TTRDP explored the possibility of a smaller constellation of low earth orbit satellites that was economically feasible and highly responsive to changing geo-political and performance demands. In the grand scheme, such a space based surveillance architecture can autonomously perform early-phase mission demands and functionally complement the existing ground and airborne assets, henceforth strengthening ISR infrastructure in all frontiers. The success of such a constellation design was achieved by adopting the metrics to measure surveillance performances, such as revisit interval, area coverage rate and fidelity of target detection and tracking data.

The performance goals set by TTRDP for the proposed constellation were [1]:

- a. To provide continuous coverage between 55°S and 80°N at all longitudes. The primary region of interest is between 20°N and 70°N.
- b. 10 minutes maximum revisit time between satellite passes.

An initial constellation design proposed 36 satellites distributed in 12 orbital planes. Performance assessment tools such as STK and SimLab verified that the concept design's orbital and constellation parameters produced satisfactory performance. Further results proved that an alternate constellation with 27 satellites in nine orbital planes at a lower inclination could also satisfy the performance goals, with gaps at the poles. The reduction in the number of satellites required for the constellation from 36 to 27 represents a significant cost reduction. Therefore, the 27 satellite constellation was adopted as the principle design for further assessment and analysis study, in order to bring the concept to reality. Figure 1 illustrates constellation orbital parameters.

This report summarizes the facts and figures obtained by evaluating the different constellation design patterns that eventually drive the effects of cost versus coverage. The optimization of global coverage distribution, AOI response time and sensor performance with cost, dictates viability assessments that are thoroughly exercised as various test cases, explained under sections 3 to 5.

This report provides descriptions of the two modelling tools, STK and SimLab, adopted to perform evaluation on the two constellation design patterns. A preliminary description is presented on the elements and assets that go into building the two performance models, one for coverage performance on an AOI and the other on a global scale. A detailed description that is presented on the sensors, satellite platforms and constellation orbital design parameters supplements the preliminary description. The assessment results, in the form of actual facts and figures, are presented in section 5 of this report.

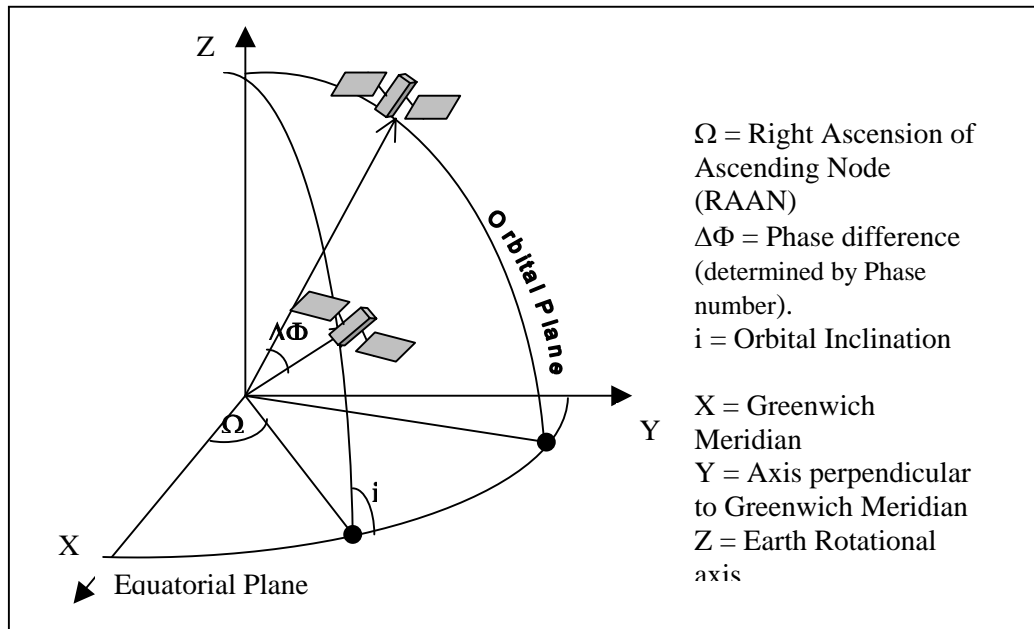


Figure 1. Orbit orientation parameters

2. Model Evaluation Tool Description

Performance assessment modelling tools are essentially a one-stop computing and simulation facility that allows an analyst to:

- Incorporate all assets of an ISR infrastructure;
- Configure the engineering attributes of each ISR asset;
- Configure the entities that are surveilled upon, such as targets within an AOI;
- Configure surveillance accessories such as command and control, environment and noise models that are relevant to effectively exercising the performance assessment evaluation scenario;
- Enable the events that cumulatively trigger the state transitions of all players within a modelled surveillance scenario;
- Enter the duration of a simulation run; and
- Generate statistical quantifications measuring coverage, detection and tracking performance.

SimLab and STK, described under sections 2.1 and 2.2, are the two chosen modelling tools, selectively configured to evaluate both constellation patterns, and to extract multi-faceted performance assessment data. The data then undergoes statistical treatment and are analyzed to quantify the MOP.

2.1 Satellite Tool Kit

STK is a Commercial Off-The-Shelf (COTS) software product, developed by Analytical Graphics Inc., (AGI). STK offers a suite of satellite, sensors, target and coverage model entities for building high-level early-phase performance assessment models.

STK provides the analytical engine to calculate the data and dynamically display 2-dimensional and 3-dimensional ISR assets, overlaid on maps, giving an exceptional look and feel environment of any surveillance scenario. STK's core capabilities, relevant to modelling a performance assessment scenario include:

- Ephemeris data generation using MSGP4 orbit propagator;
- Configure constellation of satellite and its orbital parameters;
- Defining the boundaries and spatial resolution of the coverage area, globally or by latitude bounds;
- Sensor coverage analysis tool, to deduce the figures of merit that measure the quality of coverage.

However, tracking, detection, beam scheduling, energy and many other subtle and detailed surveillance aspects are not modelled and assessed using STK due to lack of support [2].

2.2 Simulation Laboratory (SimLab)

Developed and maintained by DRDC-Ottawa, Simulation Laboratory (SIMLAB) is a secure computing facility that enables the simulation of a space based radar performance model and a whole range of other ISR models *en suite*. Some of the salient features of SimLab that justify its choice for modelling the constellation designs and performing viability assessment are [2]:

- It comprehensively simulates the functionality of any planned futuristic defence system with space based radar surveillance capability, over a single or a constellation of satellite platforms;
- It includes other assets such as, ground and airborne sensors, command and control centres, communication and data relay satellites that are all an integral part of a defence system infrastructure;
- That the surveillance performance can be assessed at threat-level conflicts. Building such a mission critical scenario is made possible by incorporating readily available:
 - Target models, both airborne and surface, with onboard jamming capabilities that move according to pre-programmed flight paths;
 - Interceptors, that can be directed towards hostile targets;
 - IR models, enabling target detection using infrared radiation sensors;
 - Cloud and clutter models to simulate signal attenuation.
 - Environmental modelling that manages information such as sun position and local visibility required by other models.
- The granularity of configuration that SimLab provides is at the level of:
 - Radar waveform parameters such as:
 - Pulse integration methods;
 - Duration of dwell; and
 - Pulse Repetition Frequency (PRF).
 - Radar beam scheduling parameters such as:
 - Revisit interval;
 - Fence (a geographic boundary) location; and
 - Fence priority.
 - Radar antenna parameters such as:
 - Antenna type;

- Transmitter and receiver aperture type and level of efficiency;
and
 - Transmitter and receiver height, width and shape.
- An energy model that calculates the energy available and amount expelled during a pre-determined surveillance mission;
- Advanced detection and tracking algorithms;
- Track fusion capability;
- Track hand-off capability;
- Customized statistical tools to validate and assess design objectives; and
- SimLab's inherent design provides great flexibility to customize any conceivable surveillance scenario.

3. Scenario Engineering Attributes

The constellation architecture coupled with mission objectives, concept design and performance goals, typically, determine the engineering attributes in constructing and simulating Space-based surveillance scenarios. The scenario engineering attributes are essentially the configuration parametric values, chosen based on the design a goal that eventually shapes the behaviour of sensor's operation and scenario execution results.

3.1 Sensor Design

The sensor was modelled based on the design outlined in the TTRDP concept alpha report [1]. Within the context of a chosen performance-modelling tool, for example SimLab, the sensor design effectively boils-down to choosing the right configuration parametric values of a space based radar instance. Table 1 provides typical initialization values:

Table 1. Typical scenario-wide sensor characteristics

ATTRIBUTES	VALUES
Antenna type	Phased Array
Transmitter and Receiver aperture width	2.5 m
Transmitter and Receiver aperture length	32 m
Transmitter and Receiver aperture type	Rectangular
Antenna elevation and azimuth	0
Transmitter power	2 kw
Clutter	Enabled
Radar wavelength	3 cm
Pulse repetitive frequency	20 KHz
Tracking	Enabled on all 219 targets

3.2 Constellation Design

Although continuous global coverage is required, every constellation design starts with determining sensor and orbital parameter values for a single satellite. With such a baseline satellite and sensor design in place, mission objectives and sensor's instrumentation performance are verified against an AOI. Upon obtaining satisfactory results in all Measure Of Effectiveness (MOE), the baseline sensor and satellite parameters are fed in to a Walker algorithm that generates a constellation of satellites with all sensors sharing the same radar characteristics [3].

The TTRDP designers used the Walker constellation algorithm as a starting point for orbital design and coverage analysis. The notation of Walker constellation T/P/F and constellation parameters, RAAN spread and Inclination are defined as:

- number of satellites (T),
- the number of planes (P) that are equally separated,
- The phasing number (F) represents the number of slots of angular measure ($360^\circ/T$) by which the easterly satellite leads the westerly satellite in an adjacent plane, where F can be any integer from zero to P-1.
 - The role of phase number F in representing a constellation pattern can be explained with an example. From a given 36/12/4 constellation pattern, the phase difference ($\Delta\Phi$) between two satellites in adjacent planes can be deduced, using:
$$\Delta\Phi = F \cdot (360^\circ/T) \text{ degrees, where } F = 4 \text{ and } T = 36.$$
$$= 4 \cdot (360/36)$$
$$= 40 \text{ degrees.}$$
- RAAN spread indicates the distribution constraint of P orbital planes along the equatorial plane. For example, a 36/12/4 constellation at 180° RAAN spread indicates 12 orbital planes evenly distributed along 180° of the equatorial plane.
- Inclination is the angle between orbital and equatorial plane and by convention is a number between -90° and $+90^\circ$. Inclination in essence determines the latitude distribution of the coverage.

3.2.1 Constellation 36/12/4

As a starting point for research and assessment activities, TTRDP adopted a 36 satellite constellation based on:

- 12 orbital planes;
- 4 Phasing number, implying 40° relative spacing between satellites in adjacent planes; and
- 180° RAAN spread, implying 15° (RAAN spread / total # of orbital planes) inter-plane spacing.

The report, referenced under [3], evaluated the MOE's of this constellation from the global coverage perspective. This report extends such evaluation and assessment to detection and tracking against the backdrop of a representative AOI with 215 targets.

3.2.2 Constellation 27/9/#

While conducting concept design research activity, the 27 satellites in 9 orbital planes at 360° RAAN spread, surfaced as a viable cost alternative. The concept alpha report proposed a 27/9/3 constellation that met the coverage

performance goals, within the primary regions of interest, with the exception of allowing coverage gaps at the poles [1].

Section 5 of this report performs phasing evaluation on all 9 phasing angles of the 27 satellite constellation, at both 180° and 360° RAAN spread. Based on the evaluation results, any potential phasing angle candidate at 360° RAAN spread that could match or surpass phasing 3 configuration predisposes extensive coverage, detection and tracking evaluation on a global scale and on a representative AOI.

4. Viability Assessment Approach

An approach to the assessment of the performance of two constellation design patterns, i.e. 27/9/# and 36/12/4, starts with constructing scenarios using the modelling tools identified in Section 2. Within the context of a performance assessment, a scenario in essence attempts to replicate the chain of events that take place during a continuous or sporadic wide-area surveillance mission. The extent of replication depends on various factors:

- Functional and operational capabilities of readily available and configurable models, namely, myriad sensors, targets, command and control, environment, cloud and clutter model, all integrated within a given assessment tool, for e.g., SimLab and STK;
- The granularity of configuration that a modelling tool permits a designer or an analyst to scale the depth of evaluation objectives; and
- Ability of underlying algorithms to produce the high fidelity output data.

Details of the scenario evaluation, its constructs, objectives and approach adopted are explained in the following sub-sections.

4.1 Approach

The following outlines the top-level approach adopted in assessing the viability and performance of the two constellation design patterns. The validation intentions identified are explained as follows:

- Object of evaluation;
 - 36/12/4 the initial design and 27/9/# the current principal design.
- Evaluation objectives, assumptions and criteria;
 - MOE on a global scale; and
 - MOE on an AOI.
- Resources and tools available to realize the evaluation objectives (refer to section 2); and
 - STK for global surveillance evaluation; and
 - SimLab for evaluating on an AOI.
- Modes and modalities for expressing the evaluated scenario results.
 - The analysis tools of STK and SimLab is used for statistically treating the scenario output results;
 - Graphical representation of the statistical data, as illustrated in section 5 of this report.

Table 2, further outlines the basic parameters of the constellation design that are shared by all scenarios, irrespective of the chosen scenario host, SimLab or STK [3]. For the purpose of analysis, the constellation parameters namely, RAAN spread and phasing angle and orbital parameters such as inclination angle and altitudes are varied within each scenario set-up. Each scenario then represents a unique constellation configuration.

Table 2. Scenario-wide constellation design parameters

PARAMETER	INITIAL CONCEPT DESIGN	NEW CONCEPT DESIGN
Number of satellites	36	27
Number of planes	12	9
Inter-Plane spacing	15°	40°
In-Plane satellite separation	120°	120°
Phasing angle	50°	40°
Inclination	85°	63.4°
Grazing angle	20-80°	20-80°
Eccentricity	0	0
Altitude	1100 Km	1213 Km
Period	107.25 minutes	109.69 minutes

4.1.1 Global Coverage

Among all the design choices that resulted from research activities, the constellation of low-earth orbit satellites eventually prevailed as the principal design choice, without compromising the existing ISR infrastructure. However, with low-earth orbits, continuous global coverage poses a primary concern which determines the MOP assessed against a given constellation design.

The objective of each scenario is to determine the MOE of global coverage at every 5° resolution and thereby quantify the constellation pattern's MOP. The stochastic parameters that measure the effectiveness of design goals, i.e., continuous coverage at varying latitude bounds are:

- Revisit Time;
 - The average duration of gaps providing coverage at every 5° resolution.
- Response Time; and

- The average time elapsed after receiving a request to observe any selected region.
- Total Coverage time.
 - The duration of accumulated global surveillance provided by the sensor's FOV at 5° resolutions within the stipulated simulation time.

Table 3, lists the scenarios that are conducted using the STK performance modelling tool for global coverage study. Scenarios 1 and 2 are mutations of constellation 27/9/# with RAAN spread and phasing angle being the mutating factors. The rationale behind exercising these scenarios is to determine the best relative spacing between satellites in adjacent planes, i.e. the phasing angle, that optimizes performance in terms of:

- Maximum total coverage;
- Quick response time; and
- Least coverage gaps.

Scenarios 3 and 4 are the mutations of scenario 27/9/3, with just RAAN spread being the mutating factor. The rationale for exercising these scenarios is to determine the extent of coverage distribution over each 5° resolution. Scenario 5 is a placeholder that might be exercised to evaluate any potential constellation configuration that closely matches or surpasses the performance of a 27/9/3 constellation. The Phasing evaluation conducted would be able to determine any such potential Phasing candidates.

Table 3: STK- Global coverage scenarios

SCENARIO NUMBER	CONSTELLATION DELTA PATTERN	RAAN SPREAD
Phasing evaluation scenarios with varying phasing angle. Orbital parameters based on the new concept design		
1.	27/9/#	360°
2	27/9/#	180°
Scenarios with varying RAAN spread. Orbital parameters based on the new concept design		
3.	27/9/3	180°
4.	27/9/3	360°
5.	27/9/# - A placeholder for any potential constellation configuration	360°
Scenarios based on the initial concept design		
6.	36/12/4	180°

4.1.2 Area Of Interest – Eastern Mediterranean Scenario

In surveillance terms, the definition of an AOI encompasses:

- A set of geographic locations forming an aerial or surface fence;
- Strategic importance due to high geo-political demands; and
- High target activity.

Besides continuous coverage over an AOI, other performance demands imposed by low-earth orbit constellation are:

- Revisit interval of 10 minutes between every satellite passes [1];
- Rate at which the new area appears into the sensors field of view, i.e. area search rate, which in-turn affects:
 - Grazing angle;
 - Dwell time;
 - Footprint size; and
 - Number of footprints.
- Radar instrument performance, which affects;
 - Coverage;
 - Detection; and
 - Tracking

Evaluation objectives to assess the impact of the above surveillance criticalities challenged by low-earth orbit constellations of either 36/12/4 or 27/9/# pattern are realized by exercising various scenarios using SimLab, as per Table 4.

Table 4. SimLab AOI scenarios

SCENARIO NUMBER	CONSTELLATION DELTA PATTERN	RAAN SPREAD
Scenarios with varying RAAN spread, based on the new concept design		
1.	27/9/3	180°
2.	27/9/3	360°
3.	27/9/# - A placeholder for any potential constellation configuration	360°
Scenarios based on initial concept design		
4.	36/12/4	180°

Other models such as communication, ground segment, fence and aerial targets provide a more realistic framework to exercise the scenarios. Table 5 explains the role and utilities of these supplementary scenario models.

Table 5. *SimLab – typical AOI scenario players*

SCENARIO MODEL INSTANCES	DESCRIPTION
Satellite Constellation	A constellation based on Walker delta pattern simulating: Surveillance of an Area of Interest; and Target detection capabilities of a Space Based Radar.
Targets	Simulates the operation and actions of 215 hostile Ground moving targets.
Fixed Fence	A fixed geographic area on the surface of the Earth that is surveilled upon by a constellation of Space Based Radars.
Air Space Manager	A SimLab specific model instance performing a coordination role.
Canada Sector Operations Control Centre	The model simulates the command and control functions capable of receiving track and status reports. Tracks received from all different sensors of the constellations are fused at this control center.
Environment	Simulates global surface clutter map.
Space Based Radar Communications	Simulates communication links between satellite constellation and Ground Segment.
Space Based Radar Ground Segment	Simulates the functionality of track initiation and processing centre for detection data, as they are reported from all Sensors within the constellation.
Sector Operations Control Centre Communications	Simulates the role of a Jammer-safe communication link between the Ground Segment and Satellite Constellation.

Table 6 shows the coordinates for an Eastern Mediterranean AOI scenario.

Table 6. *Typical AOI fence coordinates*

LATITUDE (DEG) NORTH	LONGITUDE (DEG) EAST
36.3	36.1
36.5	36.1
36.5	36.3
36.3	36.3

Table 7 shows the various types of GMTI targets that are within the scenarios. With one or more designated target IDs from each type, a total of 215 such targets are chosen to populate the AOI.

Table 7. GMTI target types

TARGET TYPE	DESCRIPTION
Tank_MC	Tank – Mechanized Company
ST_MC	Small Truck - Mechanized Company
ST_SP	Small Truck – Signals Platoon
LT_SP	Large Truck – Signals Platoon
ST_RS	Small Truck – Recce (Mechanized) Company
ST_TC	Small Truck – Tank Company
ST_ABHQ	Small Truck – 2S1 Artillery Battalion HQ
LT_AC	Large Truck – Artillery Company
ST_AC	Small Truck – Artillery Company

From the scenario perspective the Radar Cross Section (RCS) value of each target type is unique, for example the RCS of Tank_MC type targets, is 15m². The set of GMTI targets that are selected to conduct detection and tracking analysis against different constellation configurations are listed in Table 8.

Table 8. RCS values of selected targets

TARGET ID	TARGET TYPE	RCS (m ²)
1017712	Tank_MC1	15
1017765	Tank_MC2	15
1017767	ST_MC1	21
1017813	Tank_MC3	15
1017933	ST_SP	21
1017936	LT_SP	25
1023361	Tank_MC4	15
1023366	ST_MC2	21
1023633	ST_RS	21
1023681	Tank_MC5	15
1023689	ST_TC	21
1023981	ST_ABHQ	21
1023995	LT_AC	25
1024001	ST_AC	21

With tracking enabled on all AOI surveillance scenarios, SimLab generates meaningful evaluation data relevant to ISR infrastructure and performance goals. Sections 5.2 to 5.8 provide analytical details and graphical representations on the MOE obtained by exercising the AOI scenarios.

However, it should be noted that the fidelity of scenario execution results are limited by the functional restrictions of SimLab models and the extent of real-world surveillance domain they replicate.

5. Performance Assessment – Facts and Figures

Model instances are configured to generate global coverage and AOI scenarios, on STK and SimLab respectively. The simulation output data from STK and SimLab are summarized in the following sub-sections for detailed analytical study.

5.1 Global Coverage Study

As per section 3 and 4, the global coverage scenarios with varying RAAN spread are set-up and exercised using STK. Each scenario is exercised for 24 hours duration, with simulation epoch time set to 12:00:00:00 1st April 2010.

The STK analysis tool is used to measure the quality of coverage. The criteria for measuring the quality and the characteristics of each of the scenario results are explained under section 3.1.1 of this report. Some of the key assumptions and constraints made under global coverage study, using STK are:

- For the purpose of global coverage study, the scope of sensor design is limited to only configuring the inner and outer angles that determine the sensor's FOV. The inner and outer angles are computed from minimum and maximum grazing angles that are part of pre-determined set of design parameters, as per Table 2; hence, no target activity is accounted for while assessing the scenario output data.
- The coverage goals are embedded in the constellation rather than in the individual satellites; and
- The constellation exhibits emergent behaviour.

Having established the simulation technique, the following sub-sections present coverage statistics to evaluate the quality of coverage.

5.1.1 Constellation Phasing Evaluation

The rationale behind phasing evaluation is the determination of the optimum inter-satellite separation between adjacent planes that dictates uniformity in coverage distribution. In any given constellation pattern, there are as many phasing configurations as there are number of orbits that are evaluated against the following figures of merits, i.e. revisit interval, response and total coverage time. The phasing analysis for 36/12/# has been already conducted and the evaluation results are published in reference [3]. The following sections of this report use only the results of 36/12/# for the sake of comparative analysis. As part of viability assessment, the scenarios based on 27/9/# constellation at 180° and 360° RAAN spreads are conducted using the STK tool. The resulting phasing effects on coverage related MOEs are charted-out.

The Table 9 shows the phasing evaluation results at 180° RAAN, which provides the quality of coverage, for each given phase factor of a 27 satellite

constellation. By visually inspecting the statistical values of revisit, response and coverage MOEs, it is observed that both 27/9/3 and 27/9/5 patterns are potential constellations.

Table 9. Phasing analysis for 27/9/# constellation at 180° RAAN spread

PHASE	REVISIT TIME (SEC)			RESPONSE TIME (SEC)			COVERAGE TIME (SEC)		
	<i>Min</i>	<i>Max</i>	<i>Avg</i>	<i>Min</i>	<i>Max</i>	<i>Avg</i>	<i>Min</i>	<i>Max</i>	<i>Avg</i>
27/9/0	792	2520	1062	189	3353	340	8280	58403	44437
27/9/1	324	1218	650	103	2968	196	25539	70332	59309
27/9/2	229	1181	421	39	2811	133	25879	74131	69049
27/9/3	176	850	304	34	2774	123	20129	74884	69614
27/9/4	260	901	321	48	2723	133	24242	70900	63414
27/9/5	170	803	340	42	2651	126	26241	76548	71698
27/9/6	273	921	464	70	3114	159	20096	73968	65894
27/9/7	492	1249	788	125	3055	238	26120	67027	56920
27/9/8	993	1371	1210	336	3123	407	23764	43791	38743

The Figure 2 graphically charts the average values of each MOE, as a function of constellation's phase factor. The graph below indicates that a 27/9/3 constellation performs better compared to other 27/9/# patterns, closely followed by 27/9/5 constellation.

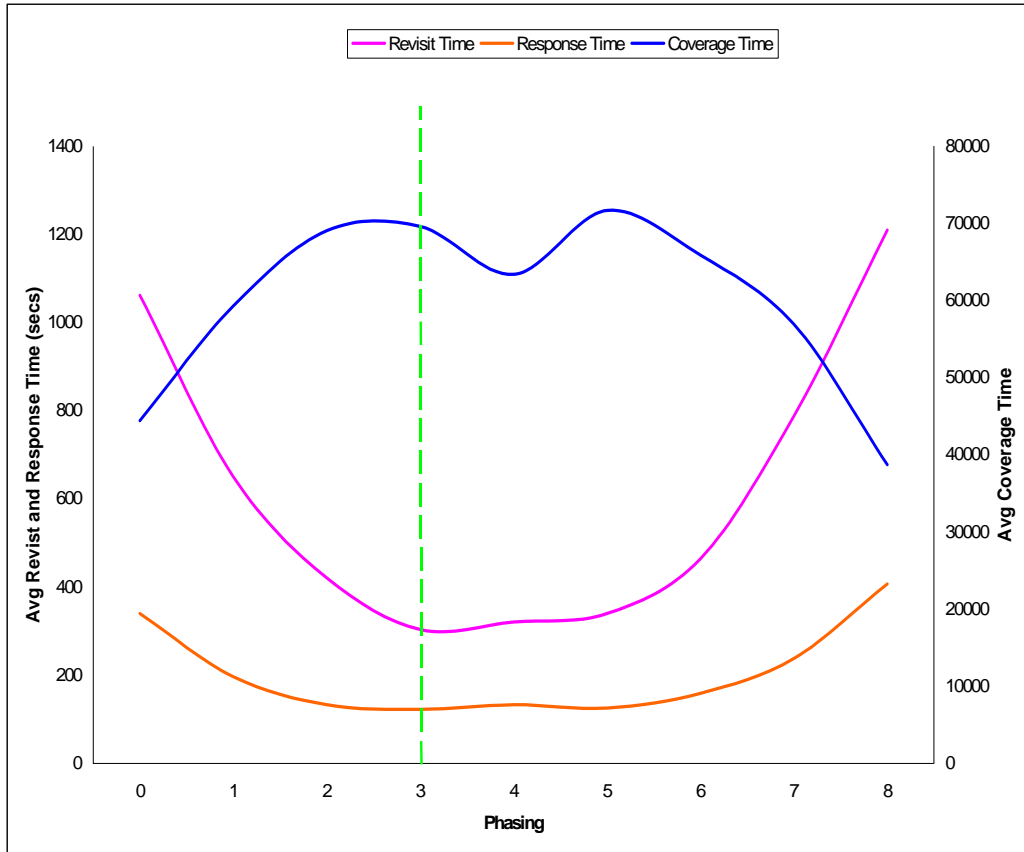


Figure 2. MOE for 27/9/# constellation at 180° RAAN spread

The Table 10 shows the phasing evaluation results of a 27 satellite constellation at 360° RAAN. By inspecting the statistical values of revisit, response and total coverage time MOEs the 27/9/5 constellation clearly emerges as a best choice.

Table 10. Phasing analysis for 27/9/# constellation at 360° RAAN spread

PHASE	REVISIT TIME (SEC)			RESPONSE TIME (SEC)			COVERAGE TIME (SEC)		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
27/9/0	75	1851	586	1	797	129	12343	84610	60599
27/9/1	0	917	334	0	443	66	28809	86400	68914
27/9/2	0	730	260	0	230	63	29062	86400	69592
27/9/3	71	485	223	1	160	34	29286	84419	70125

27/9/4	0	768	417	0	257	106	27619	86400	64561
27/9/5	0	469	146	0	209	19	29154	86400	76420
27/9/6	0	1285	565	0	350	125	29171	86400	62927
27/9/7	258	1293	778	43	362	186	29004	66137	51941
27/9/8	210	1354	761	29	553	189	25212	68668	52137

Figure 3 further reiterates Table 10, with 27/9/5 proving to provide maximum coverage time with least revisit interval and response time, in comparison to any other phasing candidates. However, it is to be noted that TTRDP's chosen constellation design is 27/9/3, even though the result showed extended revisit and response time and a moderate coverage time [1].

The results suggest the need for in-depth evaluation of the 27/9/5 constellation configuration, and also as a comparison candidate, besides other 27 and 36 satellite configurations.

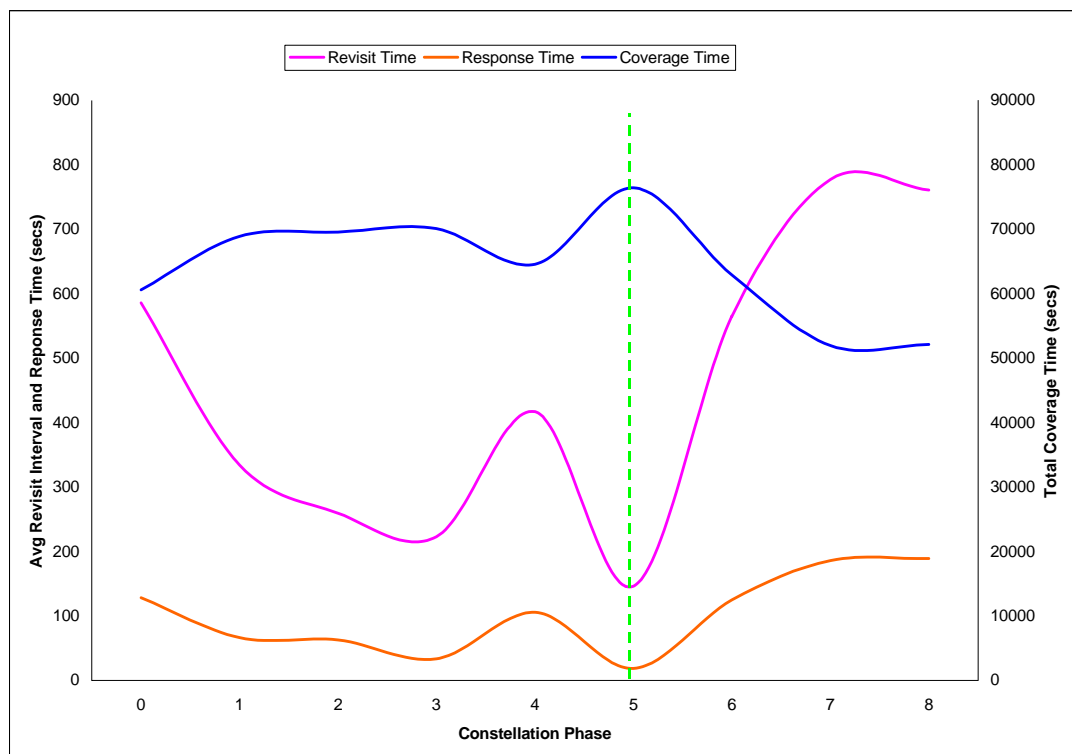


Figure 3. MOE for 27/9/# constellation at 360° RAAN spread

5.1.2 Revisit Interval

From a space surveillance perspective, the revisit interval is used to select the constellation that provides least breaks in the coverage at every 5° resolution. The MOE is assessed based on minimum, maximum and average revisit interval.

The revisit interval statistics provide the result of analysis that a performance analyst uses in comparing alternate constellation design patterns. The following analyses the revisit interval of all candidate constellation configurations from Figure 4:

- Revisit interval evaluation of a 36/12/4 constellation at 180° RAAN:
 - Between 55° S and 80° N latitude, the revisit interval does not exceed 180 seconds hence satisfying the constellation design requirements;
- Revisit interval evaluation of a 27/9/3 constellation at 180° and 360° RAAN:
 - The 27/9/3 constellation with 360° RAAN well supports the design requirements [1]. Around 10° N and S of the equator the revisit interval peaks up to well over 7 minutes, still consistent with the design requirements;
 - The 27/9/3 constellation with 180° RAAN partially meets the requirement criteria. Beyond 48° N and S of the equator, the constellation's revisit interval gradually rises to over 10 minutes, falling short of performance goals.
 - Near the equator between 32° S and 32° N, the constellation with 180° RAAN has much lower average revisit time compared to its 360° RAAN counterpart. Above and below the equator, i.e. 32° to 85° S & N latitudes the Figure 5-3 reveals that the 360° RAAN configuration has a much lower revisit interval, compared to the 180° RAAN constellation.
- Revisit interval evaluation of 27/9/5 constellation at 360° RAAN:
 - Upon conducting phasing evaluation scenarios, Figure 4 reveals that the 27/9/5 constellation has a much lower Revisit Interval between 32° N and 32° S of the equator, compared to the 27/9/3 constellation irrespective of any chosen RAAN spread.
 - Above and below the equator on both sides between 32° to 85° N & S latitudes, the revisit interval difference of 27/9/5, compared to 27/9/3, is only marginal. However, in comparison to 180° RAAN, the coverage gap is significantly greater.

- Figure 5 presents a more comprehensive picture comparing the maximum revisit intervals of 27/9/3 and 27/9/5 configurations at 360° RAAN. Figure 5 further clarifies the strikingly improved performance of the 27/9/5 constellation around 13°N and 15°S of the equator and around 32° to 85° N & S latitudes.

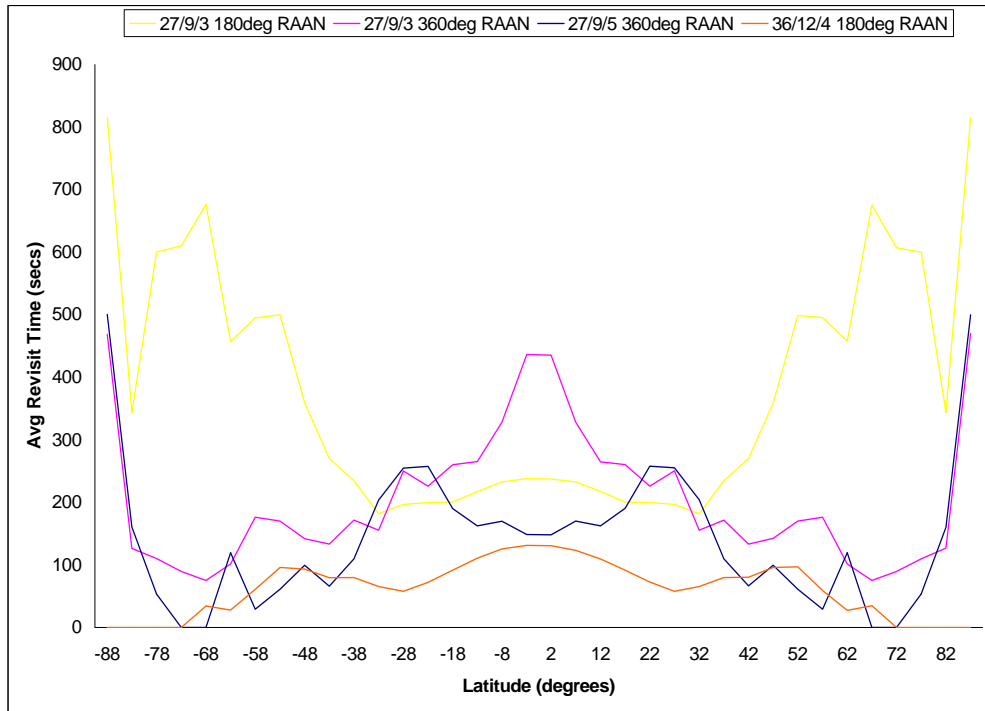


Figure 4. Average revisit interval comparative study

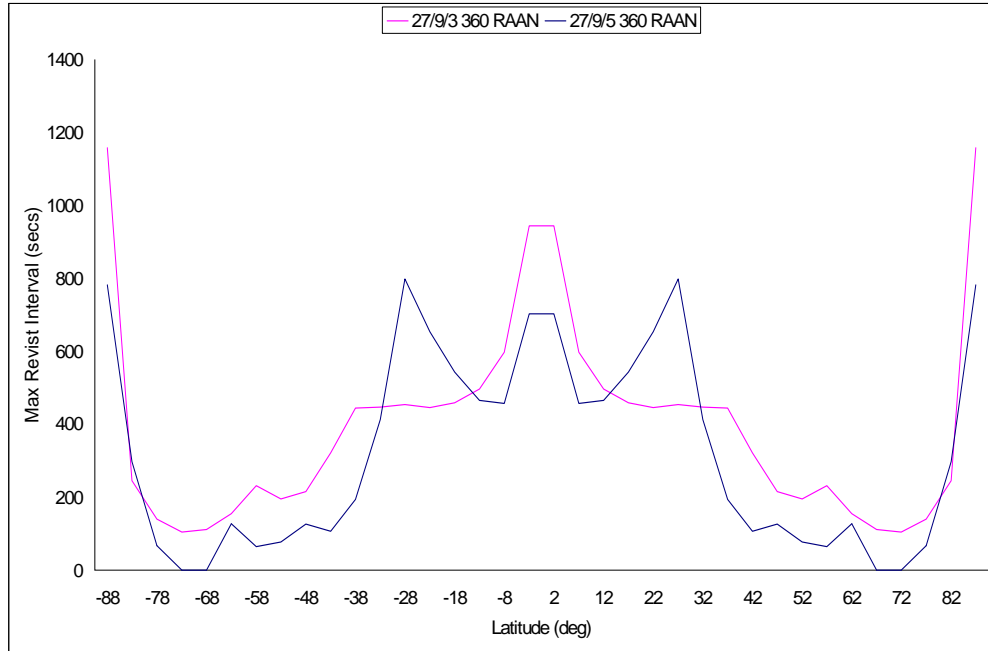


Figure 5. Maximum revisit interval comparative study

5.1.3 Response Time

The response time is a figure of merit that measures the overall responsiveness of the constellation from a system and operations perspective. The response time in turn draws its evaluation measure from coverage gaps, indicating that the larger the coverage gaps the larger the overall response time. Furthermore, counting from the time of request, the closer the satellites and the sensors are within the field of view the better are the chances of a satellite being within an AOI.

The Figure 6 elucidates the responsiveness of the constellation design that is explained as follows:

- Response time evaluation of a 36/12/4 constellation at 180° RAAN:
 - The 36 satellite constellation exhibits an instantaneous response time.
- Response time evaluation of a 27/9/3 constellation at 180° and 360° RAAN:
 - Because of the much larger coverage gaps around the equator, between 32° S and N, the response time of the 360° RAAN constellation configuration sharply rises with respect to 180° RAAN constellation configuration.

- Response time evaluation of 27/9/5 constellation at 360° RAAN:
 - In comparison to the 27/9/3 constellation at 360° RAAN, the responsiveness of the 27/9/5 between 32° S and 32° N of the equator is quicker. However, this improvement is only marginal beyond 32° to 85° S & N latitude bounds.
 - In comparison to 27/9/3 constellation at 180° RAAN, the responsiveness of 27/9/5 has been improved between 82° S and 82° N of the equator

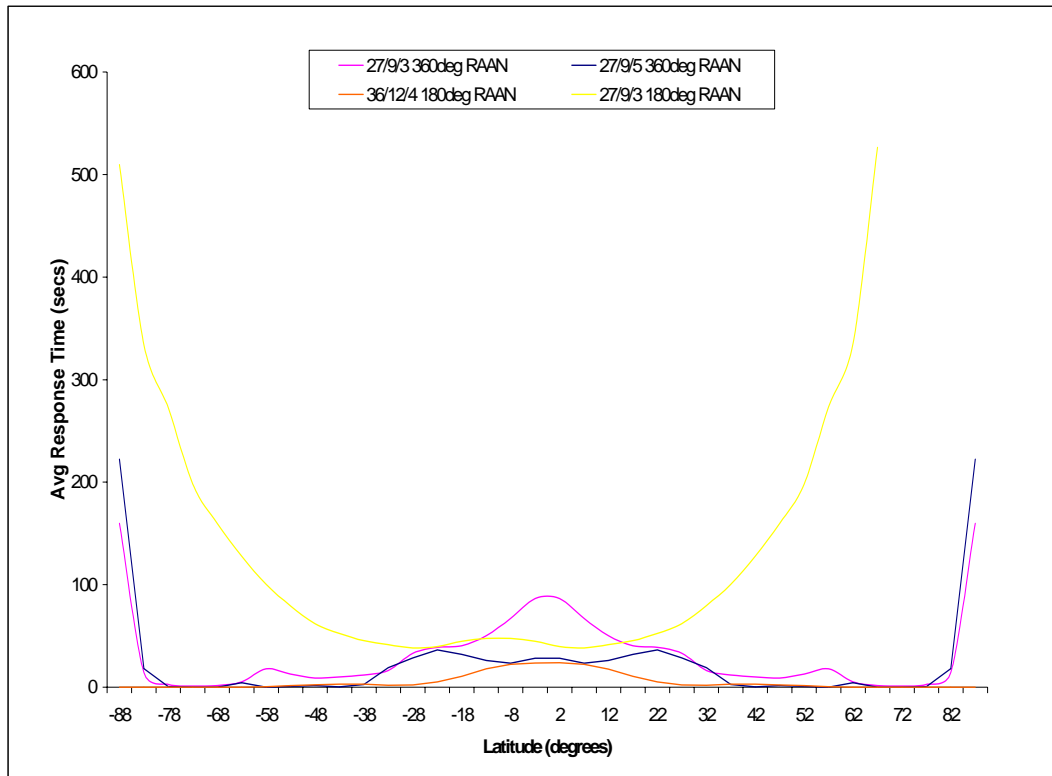


Figure 6. Response time comparative study

5.1.4 Coverage Time

The coverage time is the figure of merit that measures a given constellation’s surveillance performance. The coverage time indicates the duration of an accumulated and simultaneous FOV surveilled by a single or multiple satellites within the constellation, evaluated at 5° resolutions.

From the start to the finish of any given simulation, the summation and average of all coverage time windows represents the total coverage time and average coverage time, respectively. An average coverage time as a function of latitude, as shown in Figure 7, provides insight into the quality of coverage

that each variation of the constellation design could typically render. The following inferences can be drawn from Figure 7:

- Coverage time evaluation of a 36/12/4 constellation at 180° RAAN
 - The 36 satellite constellation exhibits nearly continuous coverage throughout the latitude distribution, from 90° N to 90° S of the equator. However, higher orbital inclination of 85°, and lower orbital altitude contributes to a slight dip in the coverage time around the equator.
- Coverage time evaluation of a 27/9/3 constellation at 180° and 360° RAAN:
 - Between 32° S and 32° N of the equator both 180° and 360° RAAN constellation configurations experience coverage loss. The advantage gained at using a higher altitude is negated by a lower orbital inclination of 63.4°, which in comparison with 36/12/4 constellation contributes to a much larger coverage loss around the equator.
 - Coverage continuity tapers-off rapidly at the poles due to lower orbital inclination.
- Coverage time evaluation of a 27/9/5 constellation at 360° RAAN:
 - The coverage time marginally increases by 5 to 10 % with respect to the 27/9/3 constellation configuration.



Figure 7. Total coverage distribution across latitude

5.2 AOI Coverage Analysis

As per sections 3 and 4, the AOI coverage scenarios with varying RAAN spread are exercised using SimLab. The scenario is simulated for the duration of 2 hours with the simulation epoch time set to 09:30:00 on 1st April 2010. The simulation epoch time is a very important parameter that essentially determines the satellite position at the start of the simulation.

The SimLab analysis tool is used to measure the quality of coverage and fidelity of radar sensor performance. Some of the key assumptions and constraints made under AOI coverage analysis are:

- Akin to global coverage study, the coverage goals are embedded in the constellation rather than in the individual satellites; and
- The radar sensor behaviour and data accuracy is limited to the detection and tracking algorithms implemented within SimLab.

Having established the simulation technique, the following sub-sections summarize the analytical data to evaluate:

- The quality of coverage; and

- Sensor performance.

5.2.1 Grazing Angle Influence On Search Parameters

Section 4.1.2 provides the rationale behind evaluating the behaviour of search parameters such as footprint size, dwell time and area search rate as a function of grazing angle.

As Figure 8 shows, Area Search Rate (ASR) tends to increase at higher grazing angles with a greater amount of area coming into sensor's field of view.

- The ASR behavioural response is largely influenced by:
 - Number of satellites in the FOV:

Above a 40° grazing angle, the 36/12/4 constellation configuration exhibits a much larger search rate in comparison to 27/9/# constellation due to a denser satellite concentration.

The orientation of satellites within the constellation causes an uneven search rate performance at certain grazing angles.
 - Varying phasing angle, with RAAN spread held constant:
 - Comparing the 27/9/3 and 27/9/5 satellite constellations, with 360° RAAN spread being held constant, Figure 8 reveals that the 27/9/3 constellation exhibits enhanced area search rate using a grazing angle between 50° and 65° . However, beyond a grazing angle of 65° , the 27/9/5 constellation configuration matches the 27/9/3 search rate performance.
 - Varying RAAN spread, with number of satellites and phasing held constant:
 - The ASR of 180° RAAN 27 satellite constellation gradually increases between 55° and 70° grazing angle. For the given representative AOI, at higher grazing angles, the constellation configuration with 180° RAAN spread performs the best, because of the smaller inter and intra orbital plane separation between satellites, resulting in a higher concentration of satellites to benefit the AOI's FOV.
 - In comparison to 180° RAAN, the 360° RAAN spread exhibits a moderate increase in search rate at a grazing angle of around 45° . However, between 55° and 70° of grazing angle the area search rate is not as high as the 180° RAAN constellation. This can be attributed to larger RAAN spread with larger inter-satellite separation resulting in fewer satellites having the AOI in their FOV.

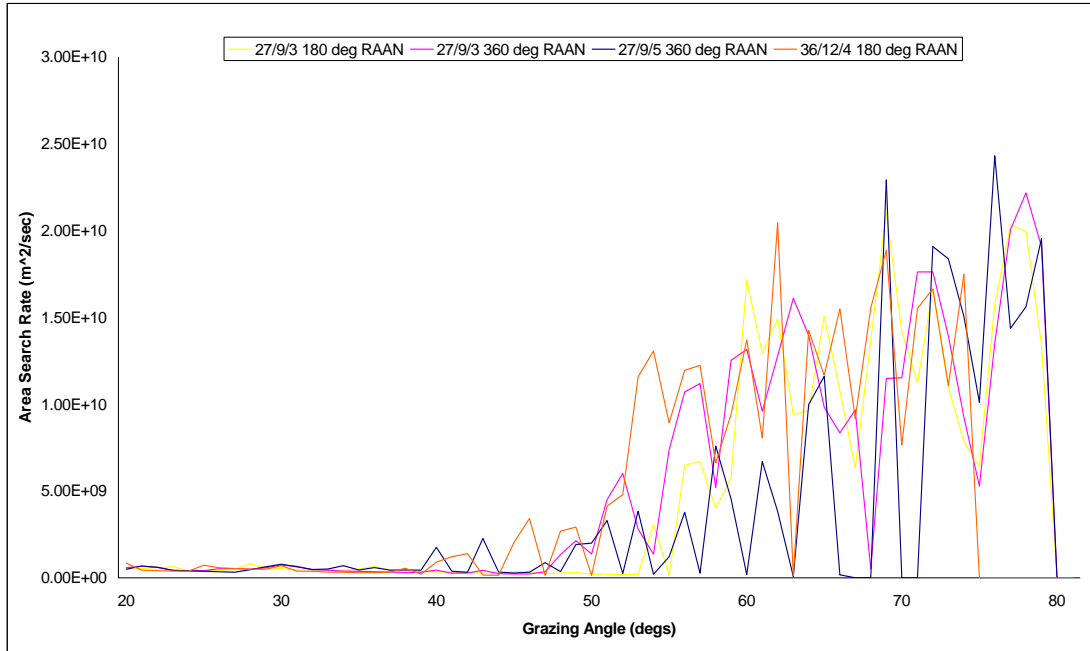


Figure 8. Area Search Rate as a function of grazing angle

Figure 9 shows dwell time as a function of grazing angle, from which the following inferences could be drawn:

- As grazing angle increases past 30⁰, the dwell time of all constellation configurations tends to drop from 80 milliseconds (ms) to 30 ms and thereafter remains uniform throughout the maximum grazing angle limit. The reason being that as the grazing angle increases the footprint size and consequently the number of dwells per footprint reduces resulting in sensor expending less dwell time for detection evaluation operations.
- At any given grazing angle, the dwell time of a 36/12/4 constellation is less than any 27/9/# constellation configuration. The lower orbital altitude of a 36/12/4 constellation configuration enhances sensor performance that in turn permits the beam scheduler to dwell less time on a per footprint basis.

The Figure 10 shows the footprint size as a function of grazing angle. As the ASR increases, the footprint size follows the same rate variation pattern to keep abreast with the AOI search goals.

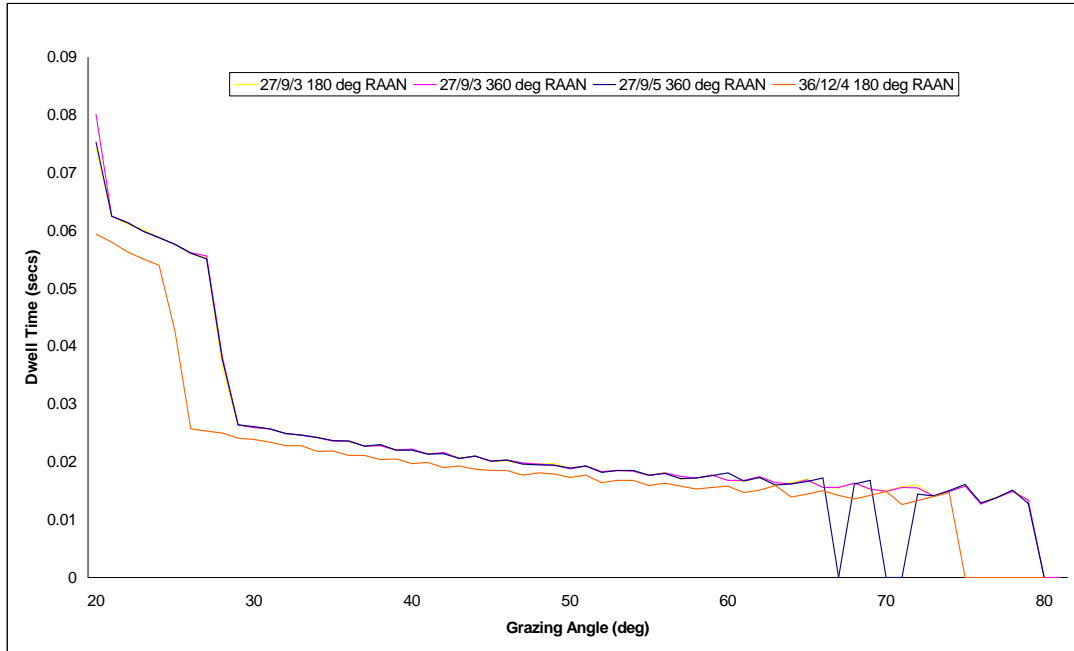


Figure 9. Dwell time as a function of grazing angle

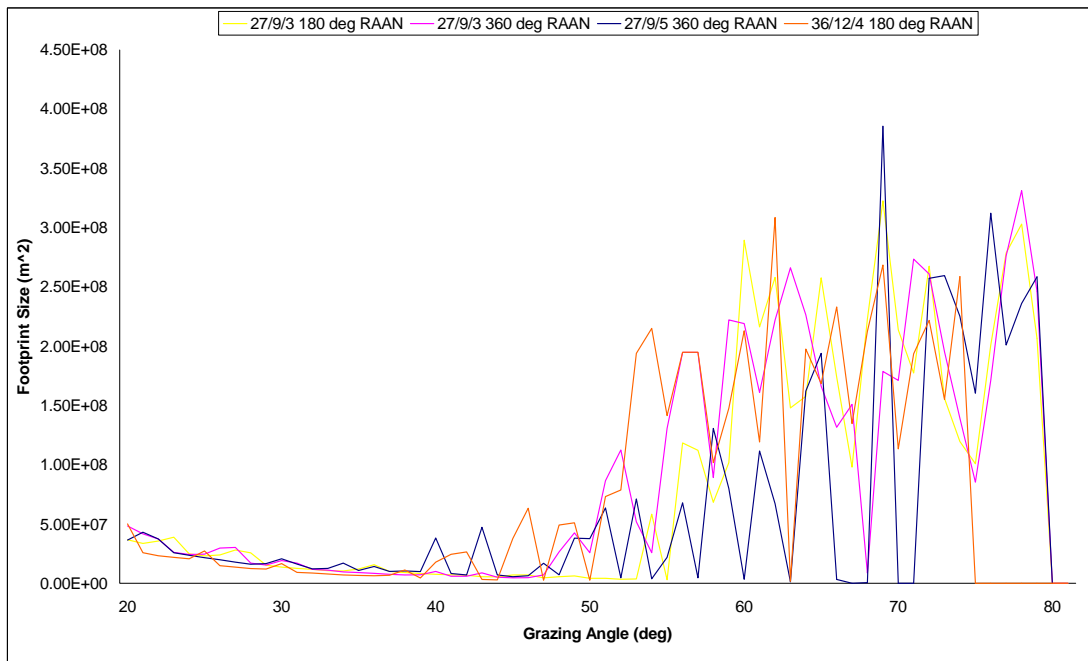


Figure 10. Footprint size as a function of grazing angle

5.2.2 Overall Detection Performance On An AOI

The overall detection statistic is used as a basis to analyze the detection performance of all 215 targets within an AOI. The mobility parameters, such as routes of each GMTI target remain unchanged across all representative AOI scenarios. However, the variations in any of the following will cause corresponding deviations in the sensor operational parameters that are calculated dynamically during the scenario execution:

- Orbital parameters such as:
 - Altitude;
 - Inclination;
 - Epoch time - satellites true position at the time of request for surveillance over an AOI.
- Constellation parameters such as:
 - Number of satellites;
 - Phasing; and
 - RAAN spread.

Some of the key sensor operational parameters that are calculated “on-the-fly” during scenario execution, are:

- Sensor FOV;
- Grazing angle;
- Environmental effects on the signal transmission path.

The above parameters directly influence detection performance. Figure 11 shows the overall detection performance of all the four candidate constellations at varying epoch time. From the global coverage assessment activity, the 27/9/5 constellation clearly surpassed the coverage performance of any 27 satellite constellation. Interestingly, over an AOI, Figure 11 reveals that a 27/9/3 constellation at 360° RAAN spread made much higher detection attempts compared to other candidate constellations. This disparity is explained as follows:

- Besides orbital and constellation parameters, the detection and tracking data largely depends on the duration of sensor’s FOV over a given area of interest. Within the stipulated 2 hours of scenario execution, the duration of sensor’s field of view in turn depends on the simulation epoch time. The epoch time in turn determines the initial position of all the satellites within the constellation.
- At the chosen epoch time, i.e. 1st April 2010 at 09:30, the 27/9/3 with 360° RAAN spread attempted maximum number of detections. The increased detection attempts resulted in an increased number of

successful detections causing shrinkage in overall detection gaps. In summary, at the chosen epoch time the 27/9/3 constellation was able to attempt 35% more detections than the 27/9/5 constellation.

- In order to ascertain the ripple effect of epoch time on the detection performance, both the 27/9/3 and the 27/9/5 constellation scenarios were exercised with simulation epoch time shifted by 6 hours ahead, i.e. to 15:30 hours. As illustrated in Figure 11, the comparison of detection attempts between 27/9/3 and 27/9/5, dropped from 35% to 2%. This means at the shifted epoch time, the 27/9/3 constellation attempted a mere 2% more detections than the 27/9/5 constellation configuration
- By shifting the epoch time to another 6 hours ahead, i.e. to 21:30 hours, detection attempt difference increased from 2% to 8%. This means, at the set epoch time the 27/9/3 constellation attempted 8% more detections than the 27/9/5 constellation configuration.

These variations in detection attempts to the shifting simulation epoch time explain the performance irregularities of the 27/9/3 and the 27/9/5 constellation over an AOI.

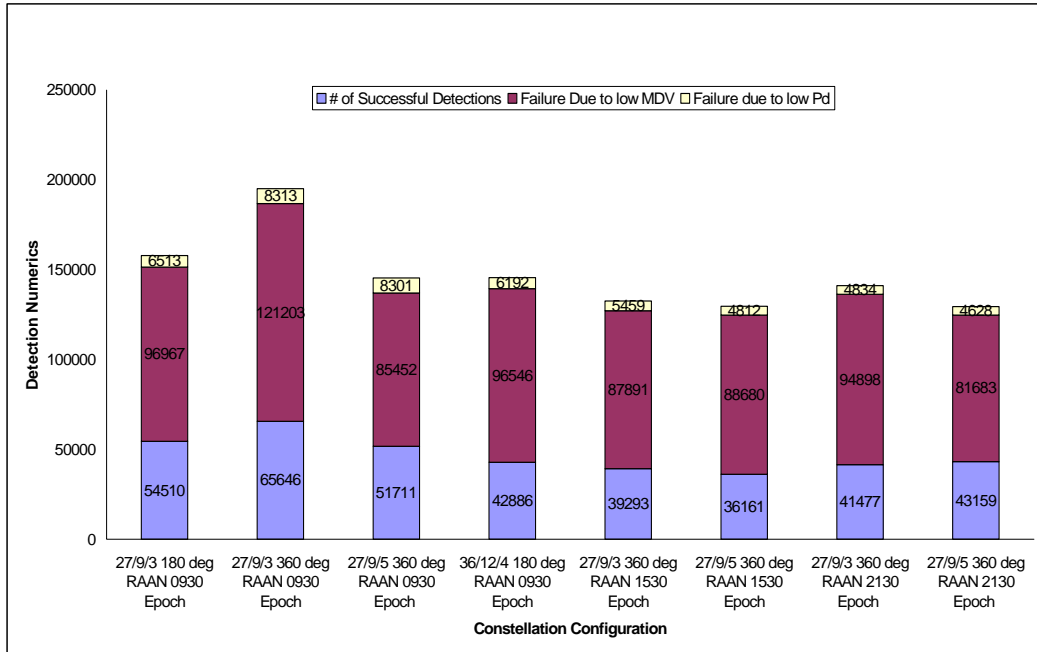


Figure 11. Epoch dependent overall detection analysis

5.2.3 Detection Performance on selected Targets

From a pool of 215 GMTI targets 14 are selected for detection analysis on an individual basis. Figure 12, further reiterates that 27/9/3 constellation with 360° RAAN spread has a better detection performance compared to the three other constellation configurations. Each of the designated targets is subjected

to much higher detection attempts at the 27/9/3, 360⁰ RAAN spread constellation configuration. This indicates that the 27/9/3 constellation has a much better field of view coupled by target's vulnerability to be detected at this satellite orientation.

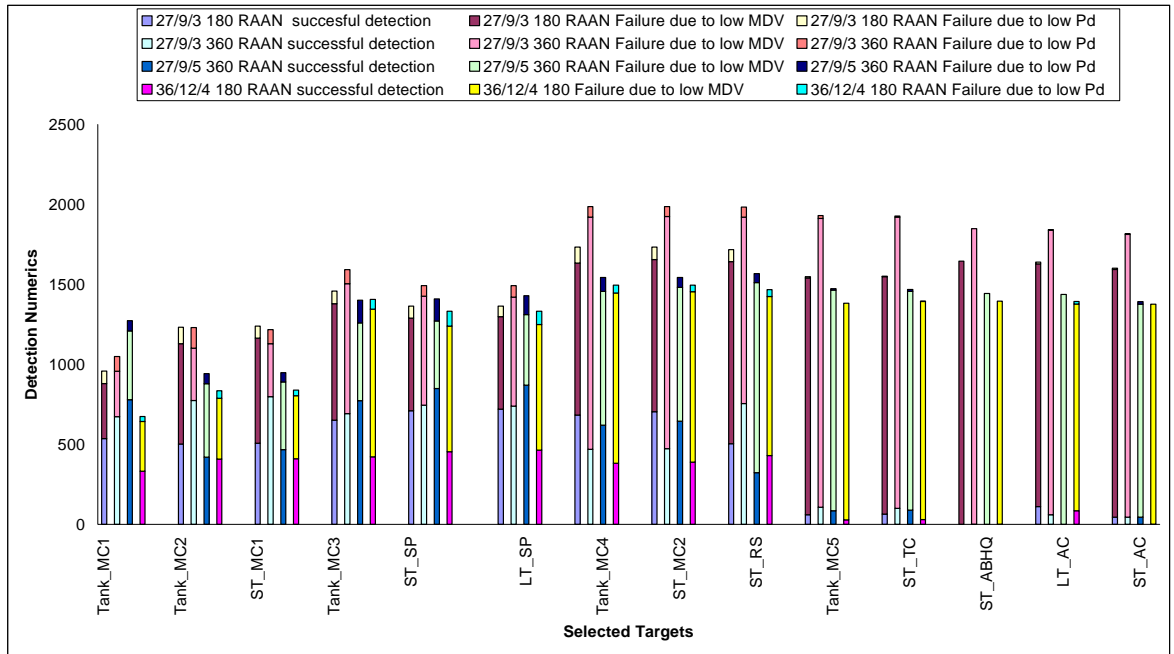


Figure 12. Comparative detection analysis on selected targets

5.2.4 Detection Gap Assessment

Besides the constellation size and varying RAAN spread, the detection gaps for individual targets, depends on various other factors, such as:

- Location of the target;
- Target mobility, i.e. detectable velocity; and
- Target RCS;

With all other orbital and constellation parameters being held constant and by merely varying the number of satellites and RAAN spread, it is shown in Figure 13 that the 27/9/3 configuration with 360⁰ RAAN spread exhibits on an average, the least detection gaps.

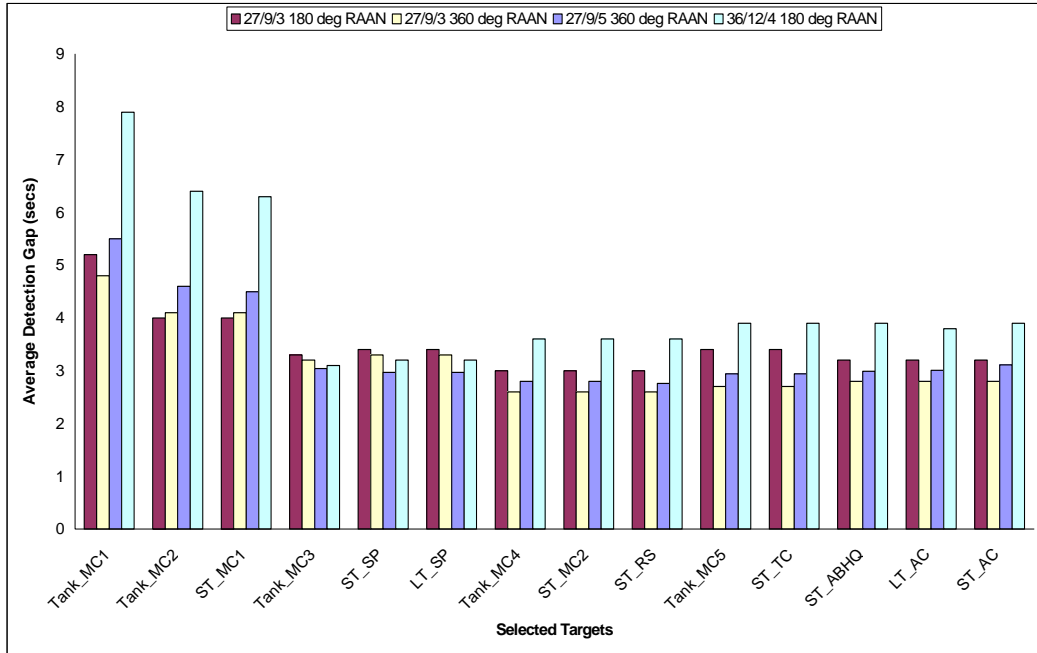


Figure 13. Average inter-detection gap time

Figure 14 shows the maximum time interval between detections. By visual inspection and by comparing all the four candidate configurations, the 36/12/4 constellation stands-out as producing the lowest maximum detection gaps followed by 27/9/3 at 360° RAAN spread. At the given epoch time, the observations could be justified as:

- The constellation size of a 36/12/4 configuration reduces the maximum duration of the AOI not being in the field of view of any satellite and hence the reduction in the maximum detection interval.
- Increasing the RAAN spread of the 27/9/3 configuration from 180° to 360° also reduces the maximum duration of the AOI not being in the field of view of any satellite and hence the reduction in detection interval, as compared with the other 27 satellite constellation sets.

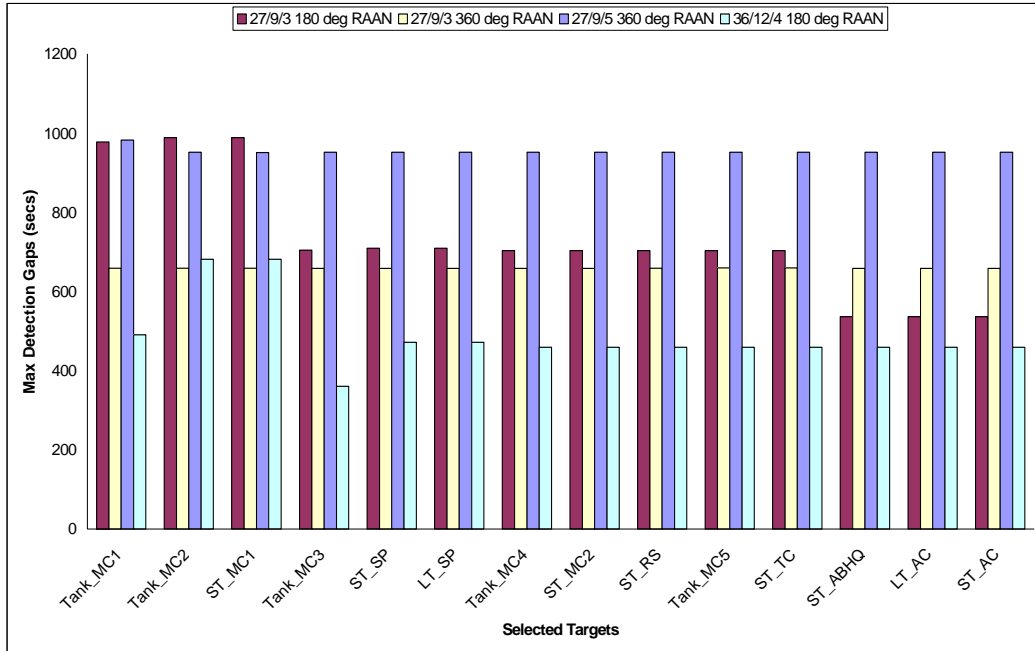


Figure 14. Maximum inter-detection gap time

5.2.5 Overall Tracking Performance on an AOI

Detection performance assessment eventually leads to tracking. Within an AOI surveillance scenario under SimLab, the events that lead to track processing, are:

- Successfully validated detections against a target;
- Track initiation;
- Track validation; and
- Track assignment to those sensors coming into the AOI field of view.

Essentially, the parameters, sources and criteria that stimulates optimizes track processing are:

- Constellation parameters such as
 - Number of satellites;
 - Distribution of satellites over the orbital planes;
- Orbital parameters such as:
 - Altitude;
 - Inclination.
- Sensor instrument performance such as:

- Antenna design parameters;
- Underlying signal processing during and after detection; and
- Fidelity of tracking algorithms.

An enhanced detection performance leads to an improvement in track initiation and track processing. From a constellation point of view the impact caused by varying the number of satellites and RAAN spread on tracking and track processing are statistically analysed in this section.

From Figure 15, comparing overall tracking performance across all four constellation configurations, the 27/9/3 configuration with 360° RAAN spread excels at initiating total number tracks. Figure 15 also shows that the 27/9/3 configuration cumulatively expends more time in tracking processing of all the assigned GMTI targets that are within the AOI fence. At a given epoch time, the following further elucidates the target tracking statistics from Figure 15:

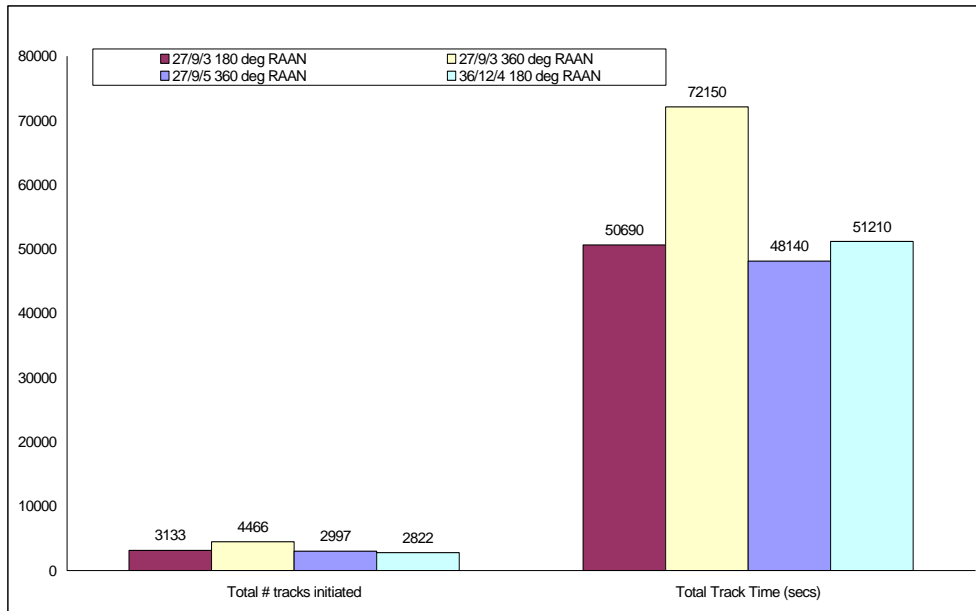


Figure 15. Overall track statistics on 215 targets

- At the given representative AOI, the 360° RAAN spread of a 27/9/3 satellite configuration results in an exact grazing angle and swath-width for the AOI to be in the satellite's field of view permitting longer dwell and an increased Probability of detection (P_d). This results in highest total track time utilized as compared to other constellation configurations.
- The tracking performance of a 36/12/4 configuration with its larger constellation size still falls behind 27/9/3 360° RAAN configurations. This again is attributed to the satellite orientation at the simulation epoch time.

As seen from Figure 16, the constellation patterns have only a marginal impact on the minimum, maximum and average track time. RAAN spread has no impact on the track time statistics.

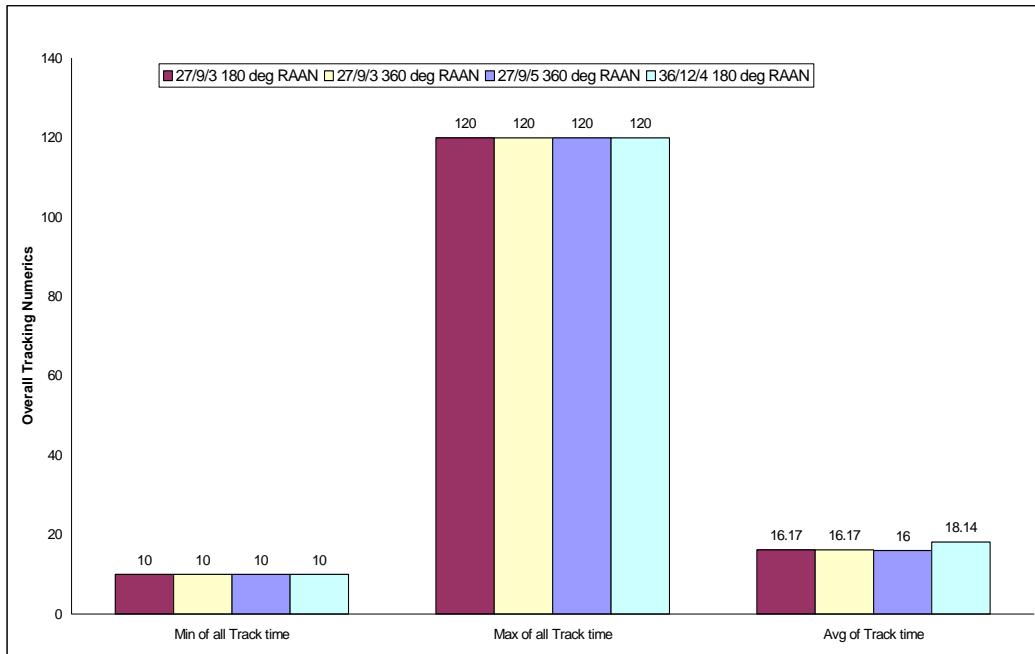


Figure 16. Overall track time

From Table 11, the following conclusions can be drawn on overall track gaps:

- Compared to other constellation configuration, the 27/9/5 configuration at 360° RAAN spread exhibits the least total track gaps. This indicates the availability of satellites as the AOI enters the field of view for the ground segment to assign tracks.
- The 27/9/3 constellation with 360° RAAN configuration experiences 13% more total track gap time, compared to 36/12/4 180°. However, the 25% reduction in the number of satellites, i.e. from 36 to 27 satellites, and hence the cost savings, far out-weighs 13% increase in total track gap time.
- The varying constellation size has no impact on the minimum track gap statistics.
- Upon accounting for the cumulative effects of both, the maximum and average track gaps, the 27/9/5 constellation configuration experiences least gaps while tracking, within the chosen 2 hours of scenario execution time.
- Despite its larger constellation size, the 36/12/4 configuration exhibits large coverage gaps, both maximum and the average.

Table 11. Overall track gaps

	27/9/3 180° RAAN	27/9/3 360° RAAN	27/9/5 360° RAAN	36/12/4 180° RAAN
Total Gap Time	275860	321200	257490	269400
Min of all Gaps	20	20	20	20
Max of all Gaps	1970	2560	1720	4320
Avg of all Gaps	149.2	163.93	151.70	200.16

5.2.6 Tracking Performance On Selected Targets

Similar to the detection assessment described under section 5.2.3, tracking performance is assessed in this section on an individual target basis. The rationale behind such assessment is to explore the impact a varying constellation size and RAAN spread has in tracking individual targets. This in turn has impacts on:

- Sensor’s field of view;
- Detection probabilities;
- Detection data fusion; and
- Track assignment by the ground segment.

The number of initiated tracks as shown in Figure 17, for individual targets results in following observations:

- The number of tracks initiated for each of the designated GMTI targets follows the same pattern as that of “Successful Detections” shown in Figure 12.
- The ST_ABHQ GMTI target has zero mobility. Hence, the target remains undetected.
- In-spite of larger constellation and reduced altitude, the number of valid detections and track initiations of a 36/12/4 configuration with 180° RAAN falls-short of the 27/9/3 or 27/9/5 constellation with 360° RAAN configuration. This is attributed to both simulation epoch time and higher orbital inclination and lower altitude.

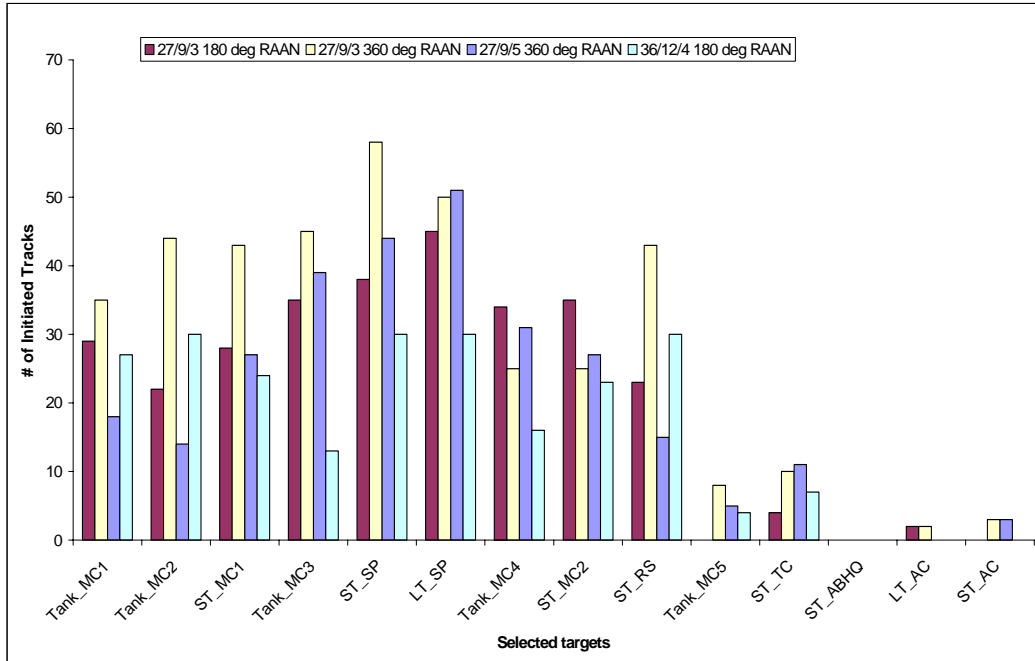


Figure 17. Number of tracks initiated

The average track time as graphed out in Figure 18, on an individual target basis, aids in drawing the following observations:

- Given the granularity of the average track time, which is in seconds, all the four constellation configurations have approximately the same overall behavioural response, with a tolerance of only 5 to 10 seconds.
- Since the designated target ST_ABHQ is stationary, none of the constellation configurations apparently produced any detection and tracking data for this target.
- For the 36/12/4 constellation configurations, the targets LT_AC and ST_AC are neither initiated nor tracked due to non-availability of sensors.

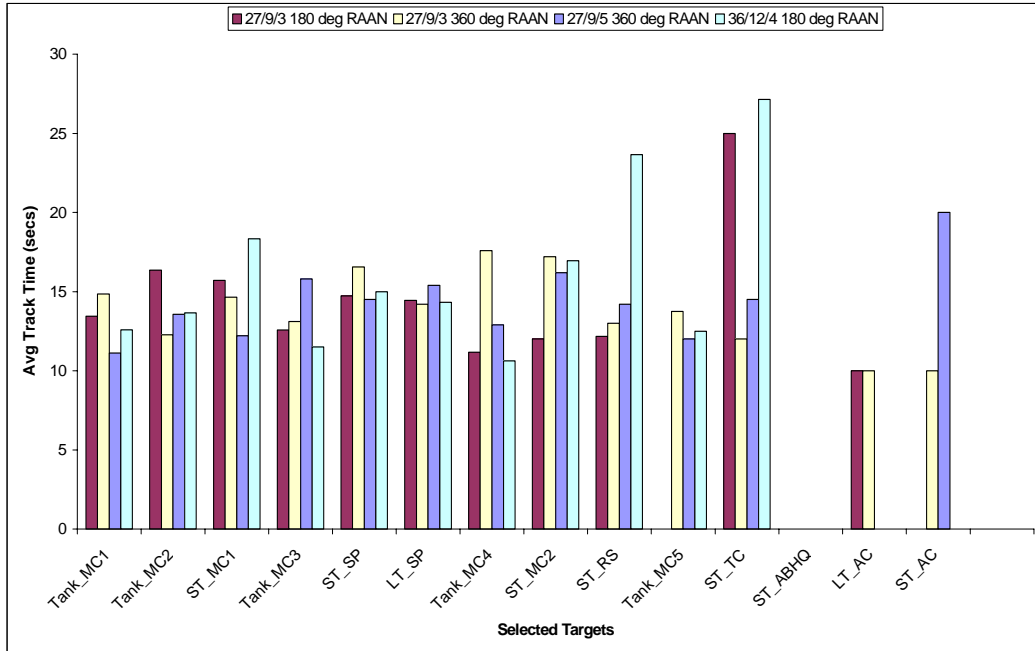


Figure 18. Average track time

The total track time of individual targets as shown in Figure 19, allows one to draw the following observations:

- From the tracking perspective, at the given simulation epoch time, the 27/9/3 configuration with 360⁰ RAAN spread makes one or more sensors available, as the AOI enters its FOV. This enables the ground segment to allocate these satellites for track updates, thus contributing to improved total track time compared to other constellation configurations.
- With its 25% larger constellation size, the 36/12/4 constellation still falls short of 27/9/3 360⁰ RAAN constellation configurations in total track time performance. The reason being:
 - The altitude reduction by 113 km coupled with packed RAAN spread of only 180⁰ takes the beam elevation and the corresponding grazing angle, of 36/12/4 constellation, away from the swath to an extent that inhibits the ground segment from assigning existing tracks to radar sensors.
 - The satellite orientation at the simulation epoch time.

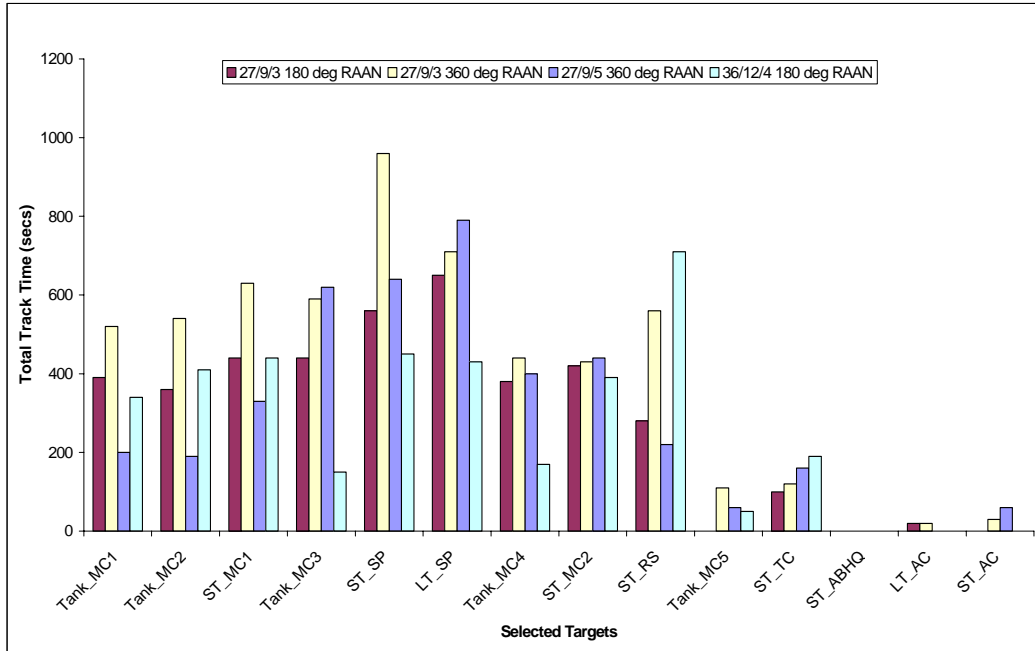


Figure 19. Total track time

5.2.7 Track Gaps

A track gap is defined as the duration between the times an existing track was dropped, due to unfavourable surveillance conditions, to the time a new track was reinitiated, on a given target. The gaps in tracking a target are primarily caused by factors such as:

- Targets not in FOV of the satellites;
- Target velocity lower than the pre-set minimum detectable velocity;
- Lower probability of detections;
- Track update interval exceeds the pre-set threshold value, causing it to be dropped.

Within the entire 2 hours of simulation, the tracks are initiated and then dropped, possibly several times, depending on various unfavourable conditions that occur during surveillance. The maximum duration that a track never was reinitiated from the time it was dropped on a given target indicates maximum track gaps as shown in Figure 20.

The average of all the durations that a track never got reinitiated from the time it was dropped indicates average track gaps as shown in Figure 21.

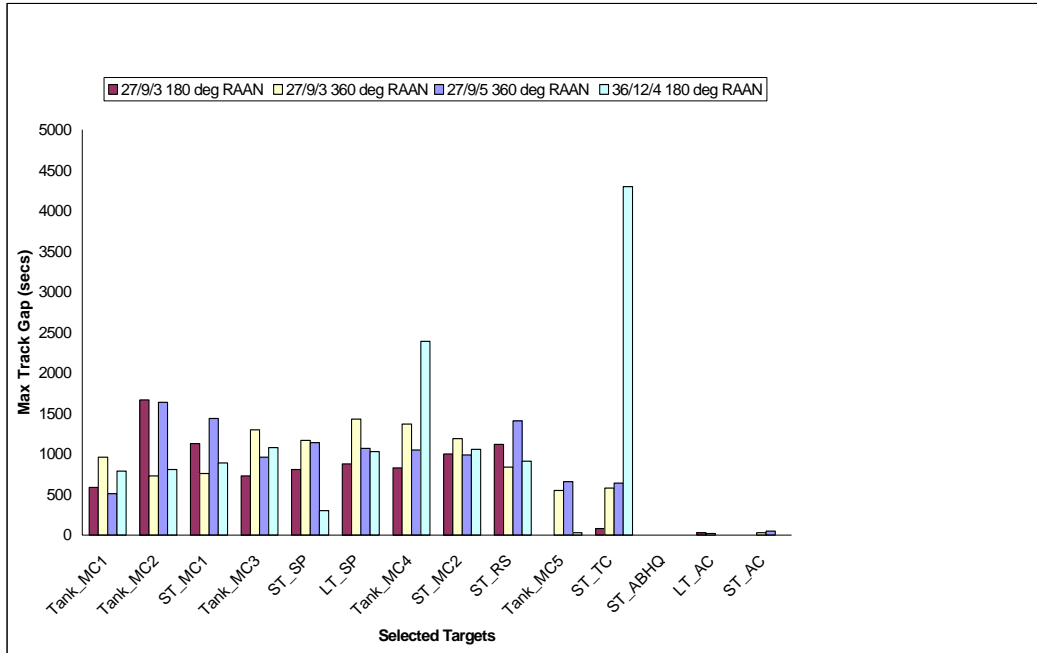


Figure 20. Maximum track gaps

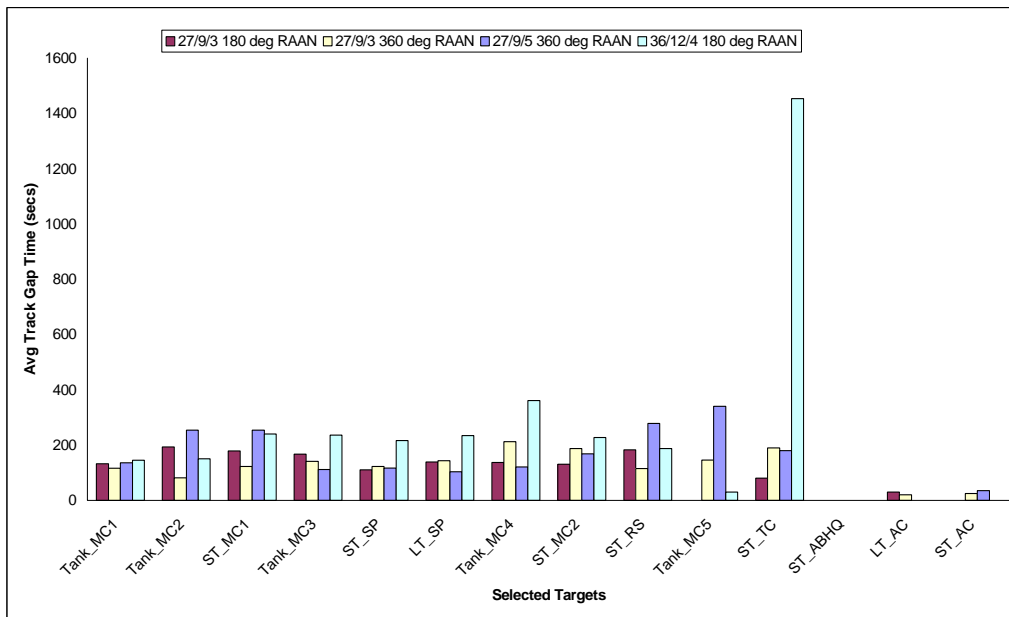


Figure 21. Average track gap time

6. Conclusions and recommendations

The assessment activity conducted at the engineering level, on the 36/12/4 and 27/9/# constellations highlighted several design trade-offs. The study measured the viability of constellation configurations at different levels of performance competencies. These findings are summarized below:

- Phasing evaluation was conducted on the 27/9/# constellation configuration at 180° RAAN spread, by varying the phasing factor from 0 to 8. At phasing slot 3, the constellation showed maximum coverage with least revisit interval and response time.
- A similar evaluation was conducted on the 27/9/# constellation, at 360° RAAN spread. At phasing 5, the constellation proved most effective and even better than the proposed 27/9/3 phasing. This prompted further investigation leading to an in-depth performance viability assessment of the 27/9/5 constellation.
- Conclusions on global coverage area, assessed at a 5° resolution:
 - The 36 satellites constellation at 180° RAAN spread produced nearly continuous coverage with negligible revisit interval and an instantaneous response time. The 27 satellite constellation at 360° RAAN spread emerged as a viable alternative, with measures of effectiveness and overall performance comparable to the 36 satellite configuration with the exception of performance at the poles. The 25% reduction in the constellation size, and hence cost, far outweighs the increased coverage gaps at the poles and a slight gap surge near the equator.
 - Among the 27 satellite configuration sets, the constellation with phasing factor 5, at 360° RAAN, produces improved total coverage time with comparably minimum revisit interval and response time.
- Assessment conclusions on an AOI:
 - Along with orbital and constellation parameters, the detection and tracking data largely depend on the duration of a sensor's field of view over a given AOI. Within the stipulated 2 hours of scenario execution, the duration of the sensor's field of view in turn depends on simulation epoch time.
 - At the chosen epoch time, i.e. 1st April 2010 09:30, the 27/9/3 constellation at 360° RAAN spread produced the maximum number of detection attempts. The increased detection attempts spurred an increased number of successful detections and total number of tracks initiations, causing shrinkage in the overall detection and track gaps.

In order to further enhance the credentials of constellation design and assessment process, several recommendations are proposed and they are as follows:

- With the baseline requirements clearly outlined, other alternate constellation algorithms need to be investigated with the possible result of constellation size reduction coupled with reduced altitude plateaus that in turn will reduce the overhead on sensor instrumentation and eventually the operational cost.
- Target leakage rates, i.e. the number of targets escaped without detection per satellite pass, in spite of its detectable velocity with a given AOI. This is another figure of merit, which directly influences the sensor design and constellation parameters.
- Terrain masking that influences target detection needs to be investigated. The evaluation of various constellation patterns and sensor performance using assessment tools that support a terrain masking feature yields realistic detection and tracking performance on hidden targets within an AOI.
- The impact on overall detection and tracking data, obtained for targets over an AOI, by varying the simulation duration, i.e. 2, 12 and 24 hours needs to be investigated. Evaluation of detection and tracking performance on three different AOIs at three extreme geographic locations on the globe is another investigative proposition. The data thus obtained can be compared against different constellation configurations to assess the influence of location on field of view and grazing angles, which in turn affects detection, track initiations and track updates.
- The non-availability of satellites and limited sensor field of view over an AOI usually results in detection and track gaps. The investigative analysis on the number of satellites that attempted detections during each single pass over an AOI and its effects on the varying epoch time provides better insight into detection and track gaps and improves assessment of constellation and sensor design parameters.

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List of symbols/abbreviations/acronyms/initialisms

ABHQ	2S1 Artillery Battalion HQ
AC	Artillery Company
AOI	Area of Interest
AGI	Analytical Graphics Inc.,
ASR	Area Search Rate
CA	Canada
COTS	Commercial Off-The Shelf
DND	Department of National Defence
DRDC	Defence Research and Development Canada
FOV	Field Of View
GMTI	Ground Moving Target Indicator
ISR	Intelligence Surveillance and Reconnaissance
LT	Large Truck
MDV	Minimum Detectable Velocity
MOE	Measure of Effectiveness
MOP	Measure of Performance
MSGP4	Merged Simplified General Perturbations
MC	Mechanized Company
ms	milliseconds
NORAD	North American Aerospace Defence System
P_d	Probability of Detection
RAAN	Right Ascension of Ascending Node
RCS	Radar Cross Section
RS	Recce (Mechanized) Company
SIMLAB	Space-Based Radar Simulation Laboratory
SP	Signals Platoon
ST	Small Truck
STK	Satellite Tool Kit
TTRDP	Tri Lateral Technology Research and Development Program
UK	United Kingdom
US	United States

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Driven by the potential military utility of a satellite constellation providing wide-area space based surveillance, the Trilateral Technology Research and Development Program (TTRDP) envisaged a framework that supports constellation concept design, assessment modeling and system feasibility studies. The concept design's "study and evolve" approach was institutionalized by formulating various teams, each oriented towards distinct research activity, to cooperatively feed on each others inferences.

The performance assessment activity kicked-off with an initial set of constellation design parameters with 36 satellites distributed in 12 orbital planes inclined at 850. The outcome of iterative research and assessment activities revealed that 27 satellites distributed in nine orbital planes at 63.40 inclination produces equally acceptable results over most of the globe. This report is the result of an effort to deduce the viability of various design trade-offs that the two sets of satellite orbital parameters and constellation patterns can render on the Measure of Performance (MOP).

Simulation Laboratory (SimLab), a simulator built in-house at DRDC Ottawa, and Satellite Tool Kit (STK), a Commercial Off-The-Shelf (COTS) tool, were used as performance modelling and assessment tools to obtain the MOP and statistically evaluate the two constellation patterns. The assessment presented in this report quantifies the MOP based on coverage, detection and tracking analysis, which SimLab exercised on a representative Area of Interest (AOI) and STK on a global scale.

With most of the satellite and sensor's parameters being held constant, a comparative performance validation was conducted against both constellation patterns. Furthermore, by varying the Right Ascension of Ascending Node (RAAN) and phasing angle, a comparative performance validation was also conducted for 27 satellite constellations.

The objective of this evaluation assessment is to reveal the combination of constellation sets that produce an acceptable performance at a reduced cost.

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Space Based Radar, Ground Moving Target Indicator (GMTI), Sensor Fusion, Intelligence, Surveillance, Reconnaissance