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Military Utility of a Limited Space-Based Radar Constellation

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Defence R&D Canada – Ottawa
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Abstract

The primary objective of this study is to assess the potential military utility of a limited Space-Based Radar (SBR) constellation for the wide-area surveillance of ground and maritime targets for the Department of National Defence (DND). As a result, it quantified the coverage performances of a limited number of SBR constellations, varying in number between one and four spacecraft, each equipped with a Surface Moving Target Indicator (SMTI) sensor. Constellation coverage performances in this case were evaluated based on revisit and response times obtained over selected areas of interest (AOI) and not performance as a function of detection, tracking, and identification of discrete surface moving targets. Satellite Tool Kit, a commercially available software suite that performs satellite performance analysis, was used to perform surveillance simulations and to produce the coverage results described in this report. The SMTI sensor parameters were obtained from specifications provided by Dr. C.E. Livingstone of DRDC Ottawa and from contract reports produced by EMS Technologies Canada, Ltd under the Space Based SMTI/SAR Systems Study. Three scenarios were used to evaluate the military potential of the simulated SBR constellations. The first considered a wide-area surveillance mission over the Canadian territorial waters with a specific interest in the surveillance of northern Canada. The next two scenarios considered a limited Canadian SBR constellation being used to augment an allied SBR constellation covering the latitudes between 60^{o}S and 60^{o}N. Accordingly, the second scenario considered a wide-area surveillance mission between latitudes 60^{o} to 90^{o}N while the third considered a wide-area surveillance mission between latitudes 60^{o}S and 60^{o}N. The results from this study indicate that a constellation consisting of two to four polar orbiting SBR satellites could be militarily useful to DND for the surveillance over Canadian territorial waters. The results also demonstrate that this same surveillance system could be employed in augmentation to national or allied surveillance sensors in a much wider intelligence, surveillance and reconnaissance (ISR) architecture.

Résumé

L'objectif principal de la présente étude est d'évaluer l'utilité militaire potentielle d'une constellation limitée de radars spatiaux (RS) pour la surveillance sur grande étendue de cibles terrestres et maritimes pour le ministère de la Défense nationale (MDN). L'étude a permis de quantifier le rendement en couverture d'un nombre limité de constellations RS, dont le nombre d'engins spatiaux variait entre un et quatre, chacun muni d'un capteur indicateur de cibles mobiles à la surface (ICMS). Dans la présente étude, le rendement en couverture des constellations a été évalué d'après les temps de survol et de réponse obtenus sur des zones d'intérêt (ZI) choisies, et non en fonction de la détection, de la poursuite et de l'identification de cibles mobiles discrètes à la surface. Un progiciel commercial d'analyse du rendement des satellites, le Satellite Tool Kit, a été utilisé pour effectuer des simulations de surveillance et pour produire les résultats de couverture décrits dans le présent rapport. Les paramètres des capteurs ICMS ont été établis à partir des spécifications fournies par C.E. Livingstone (Ph.D.) de RDDC Ottawa et des rapports produits par la société EMS Technologies Canada, Ltd dans le cadre de l'étude des systèmes ICMS/RSO spatiaux. Trois scénarios ont été utilisés pour évaluer le potentiel militaire des simulations de constellations de RS. Le premier, une mission de surveillance d'une grande étendue des eaux territoriales canadiennes, présentait un intérêt précis pour la surveillance du Nord du Canada. Les deux autres scénarios portaient sur une constellation canadienne limitée de RS utilisée pour augmenter l'effectif d'une constellation de RS alliée couvrant les latitudes entre 60^{o} S. et 60^{o} N. En conséquence, le deuxième scénario consistait en une mission de surveillance d'une grande étendue entre les latitudes 60^{o} et 90^{o} N., tandis que le troisième scénario était une mission de surveillance d'une grande étendue entre les latitudes 60^{o} S. et 60^{o} N. Les résultats de la présente étude indiquent qu'une constellation comportant de deux à quatre satellites RS en orbite polaire pourrait être utile au MDN pour la surveillance des eaux territoriales canadiennes. Les résultats ont également révélé que ce même système de surveillance pourrait aussi être employé pour augmenter l'effectif des capteurs d'une mission de surveillance alliée ou nationale, dans une architecture de renseignement, de surveillance et de reconnaissance (RSR) beaucoup plus vaste.

Executive summary

Defence R&D Canada has a Space R&D Program that supports the DND space policy objectives. As part of this program, the SBR Platform Reduction Project was mandated to assess the achievability of platform reduction for a future SBR SMTI/SAR system within the 2010 to 2015 timeframe. Under this project, various studies were initiated to derive the technological requirements as well performance trade-offs of a future SBR. In one of these studies, EMS Technologies Canada, Ltd developed a SBR SMTI/SAR antenna architecture and investigated the technical feasibility of this proposed concept. Although the efforts of this contract have produced valuable results with respect to the architecture and design of the space-based SMTI/SAR antenna, no assessment as been made on how many of these SBR platforms would be required to meet DND surveillance requirements.

The Military Utility Study was initiated under the Platform Reduction project to demonstrate the military utility of a SBR constellation intended for the wide-area surveillance of ground and maritime targets for DND. As a result, the aim of the study was to quantify the coverage performance of a constellation of satellites, varying in number between one and four spacecraft, each equipped with a SMTI sensor. Constellation coverage performances in this study were measured based on revisit and response times obtained over selected areas of interest (AOI) and not performance as a function of detection, tracking, and identification of discrete surface moving targets.

Satellite Tool Kit (STK®), a commercially available software package that performs space mission analysis, was used to design the constellation models and subsequent coverage analysis described in this report. The SMTI sensor parameters used in the simulations were based on specifications provided by Dr. C.E. Livingstone of DRDC Ottawa and on contract reports produced by EMS Technologies Canada, Ltd under the Space Based GMTI/SAR Systems Study. Constellation configurations were created using the Walker Constellation design tool in STK.

Three scenarios were used to evaluate the military potential of the simulated SBR constellations. The first considered a wide-area surveillance mission over the Canadian territorial waters with a specific interest in the surveillance of northern Canada. The next two scenarios considered a limited Canadian SBR constellation being used to augment an allied SBR constellation covering the latitudes between 60°S and 60°N. Hence, the second scenario considered a wide-area surveillance mission between latitudes 60° to 90°N while the third considered a wide-area surveillance mission between latitudes 60°S and 60°N.
The results from this study indicate that a constellation consisting of two to four SBR satellites polar orbiting satellites could be militarily useful to DND for surveillance over the Canadian territorial waters. The results also demonstrated that this same surveillance system could also be employed to augment national or allied airborne and space-based surveillance sensors in a much wider intelligence, surveillance and reconnaissance (ISR) architecture.

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R & D pour la défense Canada a un programme de R & D – espace qui appuie les objectifs de la politique spatiale du MDN. Dans le cadre de ce programme, le mandat du projet de réduction du nombre de plates-formes de RS était d'évaluer s'il était possible de réduire le nombre de plates-formes d'un futur système de RS ICMS/RSO pour la période de 2010 à 2015. Diverses études ont été entreprises dans le cadre de ce projet pour dériver les exigences technologiques ainsi que les compromis de rendement pour un futur RS. Dans l'une de ces études, la société EMS Technologies Canada, Ltd a élaboré un système de RS ICMS/RSO et a étudié la faisabilité technique de ce concept proposé. Les efforts déployés pour cette étude ont produit de précieux résultats concernant l'architecture et la conception du système ICMS/RSO spatial, mais on n'a effectué aucune évaluation du nombre de plates-formes de RS requises pour répondre aux exigences de surveillance du MDN.

L'étude sur l'utilité militaire a été entreprise dans le cadre du projet de réduction du nombre de plates-formes pour démontrer l'utilité militaire d'une constellation de RS destinée à la surveillance sur grande étendue de cibles terrestres et maritimes pour le MDN. L'objectif de l'étude était donc de quantifier le rendement en couverture d'une constellation de satellites, dont le nombre d'engins spatiaux variait entre un et quatre, chacun muni d'un capteur ICMS. Dans la présente étude, le rendement en couverture des constellations a été évalué d'après les temps de survol et de réponse obtenus sur des zones d'intérêt (ZI) choisies, et non en fonction de la détection, de la poursuite et de l'identification de cibles mobiles discrètes à la surface.

Un progiciel commercial d'analyse de missions spatiales, le Satellite Tool Kit (STK®), a été utilisé pour concevoir les modèles des constellations et faire l'analyse de la couverture subséquente décrite dans le présent rapport. Les paramètres des capteurs ICMS utilisés pour les simulations ont été établis à partir des spécifications fournies par C.E. Livingstone (Ph.D.) de RDDC Ottawa et des rapports produits par la société EMS Technologies Canada, Ltd dans le cadre de l'étude des systèmes ICMS/RSO spatiaux. Les configurations des constellations ont été créées à l'aide de l'outil de conception Walker Constellation de STK.

Trois scénarios ont été utilisés pour évaluer le potentiel militaire des simulations de constellations de RS. Le premier, une mission de surveillance d'une grande étendue des eaux territoriales canadiennes, présentait un intérêt précis pour la surveillance du Nord du Canada. Les deux autres scénarios portaient sur une constellation canadienne limitée de RS utilisée pour augmenter l'effectif d'une constellation de RS alliée couvrant les latitudes entre 60° S. et 60° N. En conséquence, le deuxième scénario consistait en une mission de surveillance d'une grande étendue entre les latitudes 60° et 90° N., tandis que le troisième scénario était une mission de surveillance d'une grande étendue entre les latitudes 60° S. et 60° N. Les résultats de la présente étude indiquent qu'une constellation comportant de deux à quatre satellites RS en orbite polaire pourrait être utile au MDN pour la surveillance des eaux territoriales canadiennes. Les résultats ont également révélé que ce même système de surveillance pourrait aussi être employé pour augmenter l'effectif des capteurs aéroportés et spatiaux d'une mission de surveillance alliée ou nationale, dans une architecture de renseignement, de surveillance et de reconnaissance (RSR) beaucoup plus vaste.

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1. Introduction

Defence R&D Canada has a Space R&D Program that supports the DND space policy objectives. As part of this program, the SBR Platform Reduction Project was mandated to demonstrate the achievability of platform reduction for a future SBR system intended for the wide area surveillance of ground and maritime targets. Under this project, various studies were initiated to derive the technological requirements as well performance trade-offs of a future SBR. In one of these studies, EMS Technologies Canada, Ltd developed a SMTI/SAR antenna architecture and investigated the technical feasibility of this proposed concept. Although this work has produced valuable results with respect to the architecture and design of the antenna, no assessment as been made on how many of these surveillance platforms would be required to fulfill future DND surveillance requirements.

1.1 Objective

The aim of this study was to quantify the coverage performances that can be obtained from a constellation of SBR satellites, varying in number between one and four spacecraft, each equipped with a SMTI sensor. The coverage performances in this study were evaluated based on revisit and response times obtained over selected AOI and not on performance as a function of detection, tracking, and identification of discrete surface moving targets.

The results of this study will contribute in determining the military utility of a limited SBR constellation intended for the wide-area surveillance of ground and maritime targets for DND.

1.2 Methodology

No surveillance mission requirements for a future SBR SMTI surveillance system were provided for this study. As a starting point, it was assumed that a limited SBR constellation would be modelled for wide area surveillance missions in the following order of priority:

- Surveillance of the Canadian northern waters (above 60^o North).

- Surveillance of the Canadian eastern and western territorial waters (up to 250 nautical miles).

- Global wide area surveillance between 60^{o}N and 90^{o}N, in augmentation to an allied SBR global surveillance system covering the lower latitudes between 60^{o}S and 60^{o}N.

- Global wide area surveillance between 60^{o}S and 60^{o}N, in augmentation to deployed CF ground based or airborne surveillance systems and/or in augmentation to allied ground based, airborne and space-based surveillance systems.

During the simulations, the results obtained for the global coverage scenarios provided valuable information as to the coverage that could be expected. However, in both of these cases, the dual-looking mode of the SMTI sensor was not be employed since surveillance was evaluated over the two global regions as wholes and not over smaller AOI within these two regions that could be targeted. In order to provide a more complete picture of constellation performances, coverage performances were evaluated over two AOI within the 60°S and 60°N global region over which the dual-looking mode could be employed. The surveillance scenarios over these AOI were based on the assumption that a Canadian SBR system would most certainly augment other national or allied surveillance platforms in support of deployed CF and/or allied operations. These two target areas were selected based on current CF deployments and are as follows:

- Surveillance on the Persian Gulf
- Surveillance in Bosnia and Herzegovina (BiH).

It was assumed that for a SBR surveillance system to be considered military useful, an average revisit time lower than 60 minutes would have to be obtained for the primary surveillance mission. Hence, all constellation optimizations were aimed at reducing the maximum and average revisit times calculated over the Canadian Northern territorial waters.

The study was performed using STK version 4.3 using the add-on Coverage Module. The STK software suite is a commercial-off-the-shelf software product developed by Analytical Graphics, Inc. (AGI). The SMTI sensor parameters were modeled in STK based on specifications provided by Dr. C.E. Livingstone of DRDC Ottawa and on contract reports produced by EMS Technologies Canada, Ltd under the Space Based SMTI/SAR Systems Study.

2. SMTI Sensor Design

2.1 SMTI Sensor Parameters

The main applications for the proposed SBR antenna are wide area land and maritime surveillance and thus the concept design is driven by the need for the primary radar sensor to provide SMTI capability. Although the radar sensor will also be capable of operating in a SAR mode, the radar sensor operating in the SMTI mode currently drives the constellation optimization process during the study. Consequently, the sensor designed in STK for this study only modeled the field of view of the electronic steered array antenna operating in a SMTI mode. More precisely, the model reproduced the scan frame within which the SMTI radar beam will search for moving targets. Annex A provides the exact parameters that were used to model the SMTI sensor within STK using the Coverage module.

In order to obtain a reliable approximation for this first coverage analysis, the SMTI sensor parameters modeled in STK were based on the actual SMTI/SAR antenna architecture developed by EMS Technologies Canada, Ltd. Accordingly, physical and geometrical parameters were all taken from the latest list of requirements (EMS Technologies, 2003). Table 1 illustrates these parameters.

Table 1. SMTI Antenna Parameters (EMS Technologies, Ltd., March 2003).

Antenna Parameter	SMTI Operation
Elevation plane size	2.5
Azimuth plane size	22 m
Mechanical bore sight elevation cant relative to nadir	37.4^o
Elevation plane scan range (relative to the mechanical bore sight)	$\pm 18.7^o$
Azimuth plane scan range (relative to the mechanical bore sight)	$\pm 45^o$
Minimum elevation angle (ε_{min})	$\approx 13.3^o$
Maximum elevation angle (ε_{max})	$\approx 67.9^o$

2.2 Dual-Looking Mode

The SBR antenna will be flown in either a left-looking or right-looking configuration. The satellite will be mechanically manoeuvred in the left or right-looking configuration to position the electronic field of regard in the optimum place before approaching a desired AOI. This will be achieved by rolling the spacecraft towards the left or towards the right of the sub-satellite track.

As illustrated at Figure 1, although the SMTI access area shows two sectors, the actual instantaneous field of view (IFOV) that the SBR SMTI sensor will view at any given time is half of the access area. By definition, the IFOV is the actual area the instrument or antenna can see at any moment. In contrast, the access area is the total area on the ground that could potentially be seen at any moment by turning the spacecraft or instrument. The time that will be required for the spacecraft to execute a roll manoeuvre is unknown at this time. For the simulations, a roll manoeuvre was assumed to require 10 minutes. This assumption is based on the time Radarsat-2 will require to complete this manoeuvre.

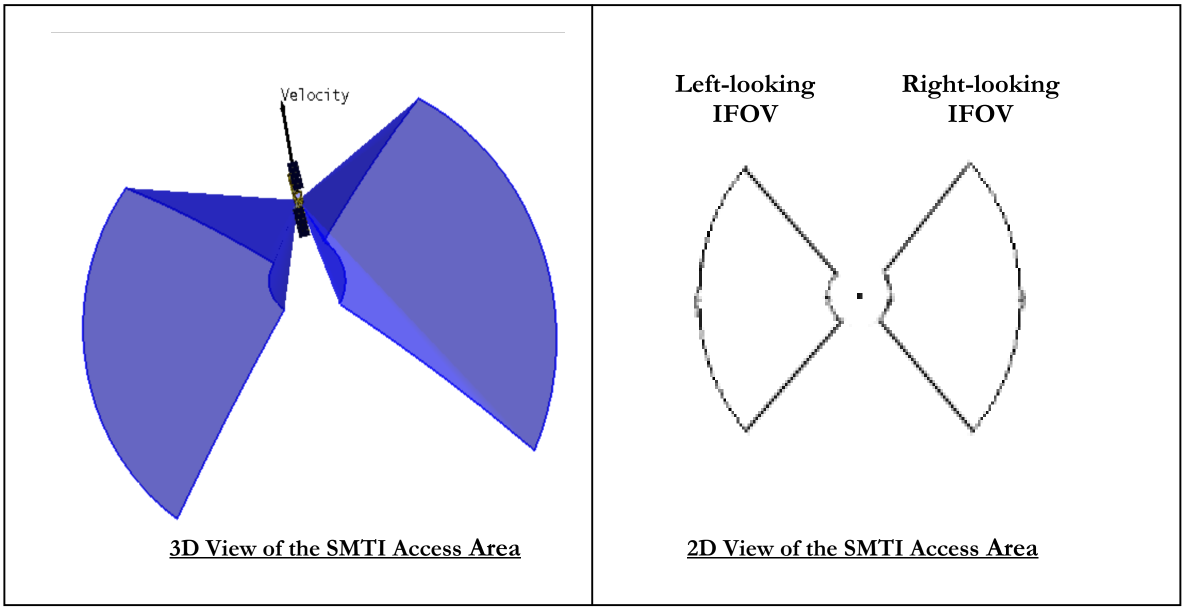

Figure 1. SMTI Access Area.

Two sets of simulation trials were conducted during this study. The first trials were conducted using a right-looking mode only. The coverage performance results for these trials were included in this report as they provide an insight as to what performance can be expected should a dual-looking mode fail once the SBR is in orbit.

The second set of simulation trials was conducted using the dual-looking mode. STK could not simulate automatically the dual side-looking mode that has been described above. Consequently, in order to include the desired dual-looking mode in the STK simulations, a simple MATLAB program was created that produced STK sensor pointing files for each of the SBR satellite within the constellations. The data required to create the pointing files were the access times between the desired AOI and both IFOV. The MATLAB program determined the pointing requirements based solely on maximum surveillance time over the desire AOI. In situation where both IFOV had access to the desire AOI, then the one with the maximal surveillance time was selected.

3. Constellation Design

3.1 Orbit and Constellation Design

The constellation design process began with the design of a seed orbit that was then used to create the various constellation configurations from which coverage performance would be gathered. The seed orbit was optimized under the assumption that the SBR constellation would be designed to meet national surveillance requirements such as the surveillance of the Canadian northern territorial water. Hence, the space segment of the surveillance constellation will consist of polar or highly inclined SBR satellites in order to provide maximum coverage over the Canadian territory. Annex A provides the parameter of the seed orbit used for all of the simulations.

As the goal of the study was to obtain an idea of coverage that various constellation would provide, very little time was spent on optimizing the seed orbit to maximize coverage. Orbit and constellation design encompasses an extremely large trade space, and thus, many of the constellation parameters were kept constant in order to limit the time of the optimization process. Table 2 provides the set parameters that were selected as an initial point in the trade space design of the SBR constellation.

Table 2. SBR Orbit and Constellation Parameters

System Parameter	Current Assumption
Constellation: Possible number of satellites: Possible number of planes:	 1 - 4 satellites 1 – 4 orbital planes
Constellation pattern	Walker
Orbital altitude (h)	Approximately 1100 km
Eccentricity (e)	0.0
Orbital inclination (i)	80^o – 100^o

It was decided at the beginning of the study that the constellation pattern employed would be Walker constellation patterns. Walker constellations are a common type of constellation that attempts to maximize coverage for satellites in circular orbits at a common altitude and inclination. The design goal of Walker constellations is to provide continuous multiple coverage of the entire earth using the smallest number of satellites in symmetric orbits. Although it has been demonstrated that Walker orbits are not optimal for irregular sensor footprint, these constellation patterns proved the most economical means to demonstrate rapidly the coverage performance of the various constellations. Table 3 lists the constellations that were analyzed.

Table 3. Evaluated Constellation Configurations

Designation	Number of satellites	Number of planes
First Set of Simulation Runs (Right-Looking Mode Only)		
1/1	1	1
2/1	2	1
2/2	2	2
3/1	3	1
3/3	3	3
4/4	4	1
4/2	4	2
4/4	4	4
Second Set of Simulation Runs (Dual-Looking Mode Enabled)		
2/2 D	2	2
3/3 D	3	3
4/2 D	4	2
4/4 D	4	4

Constellation design, launch factors, orbit manoeuvring and constellation maintenance will be critical aspects of the design of an actual SBR constellation that will affect both the spacecraft design and the cost of the whole program. However, these were considered to be out of the scope of the current preliminary study and thus, were not considered at all in this study.

The date 1 April 2010 was arbitrarily selected as a target day for SBR concept evaluation. All simulations were based on a one-month period, more precisely from 1 to 30 April 2010.

3.2 Areas of Interest

This section describes the AOI that were created within the scenarios. These were designed according to the wide area surveillance missions that were described in section 1.2. Five AOI were designed to assist in the evaluation of the coverage performance of the various constellations. These AOI are:

- Canada (sub-divided into Canada North, Canada East and Canada West).
- Global coverage between latitudes 60°N and 75°N.
- Global coverage between latitudes 60°S and 60°N.
- Persian Gulf
- BiH

3.2.1 Canada

As described earlier, the primary surveillance mission of the SBR constellation was assumed to be over the Canadian northern waters. Since the Canadian territory spans many degrees of latitude and because coverage was expected to vary as a function of latitude, the Canadian AOI was divided into three separate AOI (see Figure 2):

a. Canada North. This surveillance scenario was aimed at evaluating the coverage performance obtained over the northern Canadian territory above 60^{o}N latitude.

b. Canada East. This surveillance scenario was aimed at analyzing coverage over the eastern Canadian territorial waters up to a distance of approximately 250 nautical miles from the eastern coast.

c. Canada West. This surveillance scenario was aimed at analyzing coverage over the eastern Canadian territorial waters up to a distance of approximately 250 nautical miles from the western coast.

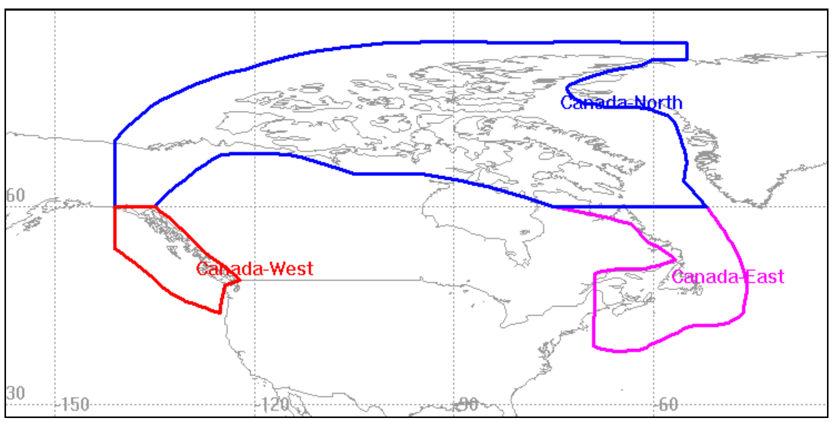

Figure 2. Canada North, East and West AOIs.

3.2.2 Global Coverage Between Latitudes 60^{o}N and 90^{o}N

Due to the geographic location of Canada, a wide area surveillance SBR system designed to cover the Canadian territory will also cover the complete northern hemisphere. As such, it was assumed that a future CF constellation of SBR surveillance satellites could also serve to augment future allied SBR surveillance systems covering the latitudes below 60^{o}N. Consequently, a third surveillance scenario was created that was aimed at evaluating the coverage performance obtained over the northern hemisphere between latitudes 60^{o}N and 90^{o}N.

3.2.3 Global Coverage Between Latitudes 60°S and 60°N

It was assumed that an actual SBR system whose primary mission is the surveillance of the Canadian territory could also be called upon to support CF elements deployed on operations anywhere in the world and/or to augment allied SMTI platforms. Since these operations could occur in any region concentrated between 60°S and 60°N latitudes, an AOI covering this region was designed.

3.2.4 Persian Gulf and Bosnia and Herzegovina

In both of the global AOI described above, the dual-looking mode of the SMTI sensor was not be employed since surveillance was evaluated over the two global regions as wholes and not over smaller AOI within these two regions that could be targeted. In order to provide a more complete picture of constellation performances, coverage performances were evaluated over two AOI within the 60°S and 60°N global region over which the dual-looking mode could be employed. These scenarios were incorporated into this study since it was assumed that a Canadian SBR system would be called upon to support CF operations in specific theatre of operations or to augment other allied SMTI platforms conducting surveillance over specific target areas. The two other target areas selected are based on current CF operations, namely OP APOLLO in the Persian Gulf and OP PALLADIUM in Bosnia and Herzegovina (BiH) (Figure 2).

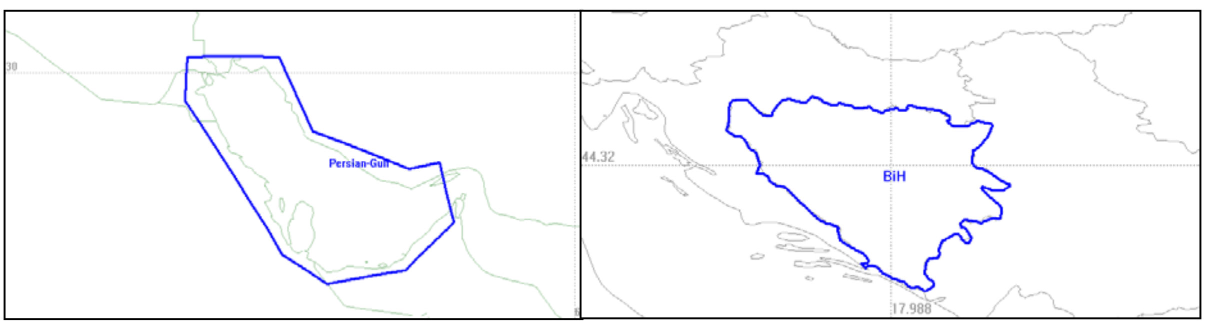

Figure 3. Persian Gulf and BiH AOI.

3.3 Figures of Merit

An important step in creating a coverage simulation is to determine the appropriate method to gather coverage statistics and to evaluate the quality of coverage. Figures of merit (FOM) are numerical mechanisms for comparing the coverage of satellites and constellations. Many FOM are available to evaluate the performance of constellations, however not a single FOM will provide an exact picture as to which is the ideal constellation configuration. Many authors differ on the most important FOM to consider when evaluating the performance of a constellation. Some consider the maximum revisit time to be the most stressing FOM to the potential mission while the average revisit time is considered to be the predominant FOM. Others state that the average response time is believed to be the best FOM since it provides a more useful measure of the end performance of the system and because it can be easily extended to include delays due to processing, communications, decision making, or the initiation of action (Wertz, 1999). In summary, all authors agree that no one coverage FOM will prove successful by itself and a combination of these is the most appropriate method of evaluating a constellation.

As this was a preliminary study aimed at quantifying the performance of a relatively low number of constellations with a varying number of satellites between one and four, only three FOM that are stated to be the most indicative of performance were retained to evaluate the coverage performances. They are as follows:

a. Maximum Revisit Time. The maximum revisit time represents the maximum duration of time that a single grid point could not be viewed by any satellite, or in other words, the maximum time between satellite revisit. From the military perspective, the maximum revisit time is the length of time a target will be unobserved. For each defined target areas, STK further divides them into regions according to the desired resolution of the coverage analysis. Consequently, a maximum revisit time is provided for each of these regions. The final results for a specific target area are a minimum, a maximum and an average value for all of the maximum revisit times collected within a specified target area. The average maximum revisit time was selected as the primary value.

b. Average Revisit Time. The average revisit time represents the average time that a single grid point could not be viewed by any satellite. Like the previous FOM, STK provides a minimum, a maximum and an average value for all of the average revisit times collected with a specified target area. The average maximum revisit time was selected as the primary data in which error bars denote the maximum and minimum values.

c. Average Response Time. The average response time is the average time from receiving a request to observe the point to the time that a satellite can actually observe the point. The average response time is believed to be the stronger FOM since it provides a more useful measure of the end performance of the system. More precisely, it can be easily extended to include delays due to processing, communications, decision-making, or the initiation of action (Wertz, 1999). The maximum response time is equal to the maximum revisit time.

All FOM values were obtained with respect to a single grid point on the globe at a resolution of one degree at the equator. STK automatically adjusts the resolution at higher latitude to ensure that the distance between each sample point remained approximately the same.

4. Constellation Evaluation

4.1 Coverage Performance Results

This section provides coverage performance results that were obtained during the simulation trials. As expected, the results showed that coverage performance is latitude dependent, improving as the latitude increased. As well, the coverage performance also improved as the number of satellites in the constellation was increased. The addition of a dual-looking mode also improved the maximum and average revisit time significantly over target areas.

4.1.1 Canada

For all three Canadian regions, the single plane constellations provide the worst performance of all the evaluated constellations, especially when the maximum revisit times are considered. As expected, the three coverage performances within the three Canadian regions varied due to the latitude dependency of the FOM. Finally, the addition of the dual-looking mode to the 2/2, 3/3, 4/2, and 4/4 constellations had a positive effect on the maximum and average revisit times but not as much on the average response time.

4.1.1.1 Canada – North

Figure 4 provides the coverage performances over the Canada North AOI.

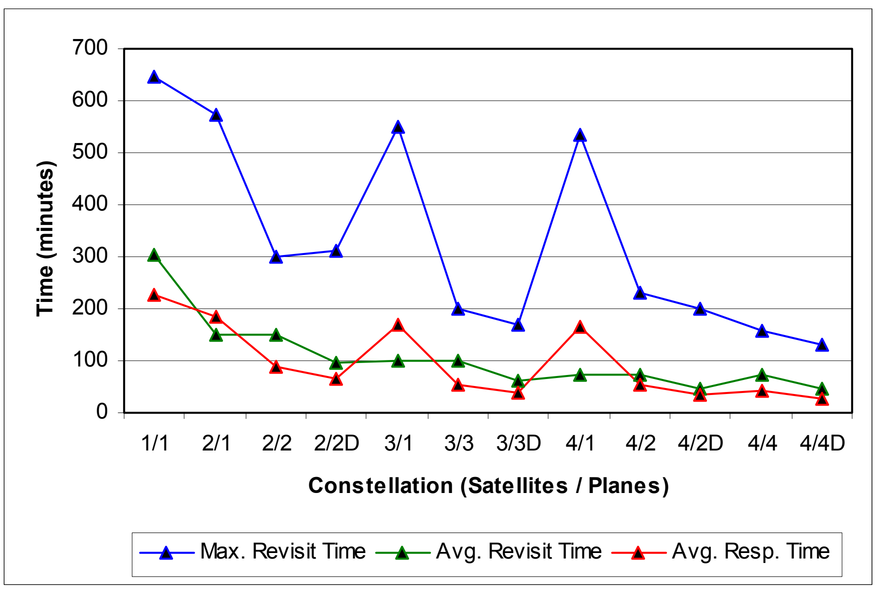

Figure 4. Canada – North: Coverage Performance

Only three constellation configurations provided an average revisit time of approximately, or below, 60 minutes over the Canada North AOI. These constellations and their specific performances are listed in Table 4. The coverage performances of the same constellation using only the right-looking mode were also provided in that table in order to better illustrate the benefits of the dual-looking mode.

Table 4. Coverage performances over Canada-North AOI.

Constellation	Avg Revisit Time (min.)	Max Revisit Time (min.)	Avg Response Time (min.)	Requirement Met
4/4D	45	130	29	YES
4/2D	45	199	35	YES
3/3D	62	169	38	YES
2/2D	96	311	64	NO
4/4	73	157	42	NO
4/2	72	231	54	NO
3/3	99	199	54	NO
2/2	150	302	88	NO

It must be noted that the 2/2 constellation using the dual-looking mode provided an average revisit time below 100 minutes. Although the assumed surveillance requirement was not met, this result indicates that this constellation could provide DND a potential military useful surveillance with reduced capability at a lower cost. This could represent an impressive savings and a compelling rationale for the continuing re-evaluation of the surveillance requirement. Of course, reducing the number of spacecraft would not only reduce the coverage performance, but also would increase the risks of mission success.

As a final point, the coverage performances over the Canada North AOI represents an average over an area spanning almost 30 degrees of latitude. Coverage performance results over specific AOI such as the Northwest Passage are expected to be better.

4.1.1.2 Canada – East and West

Figures 5 and 6 illustrate the coverage performances of the Canada East and West AOI respectively.

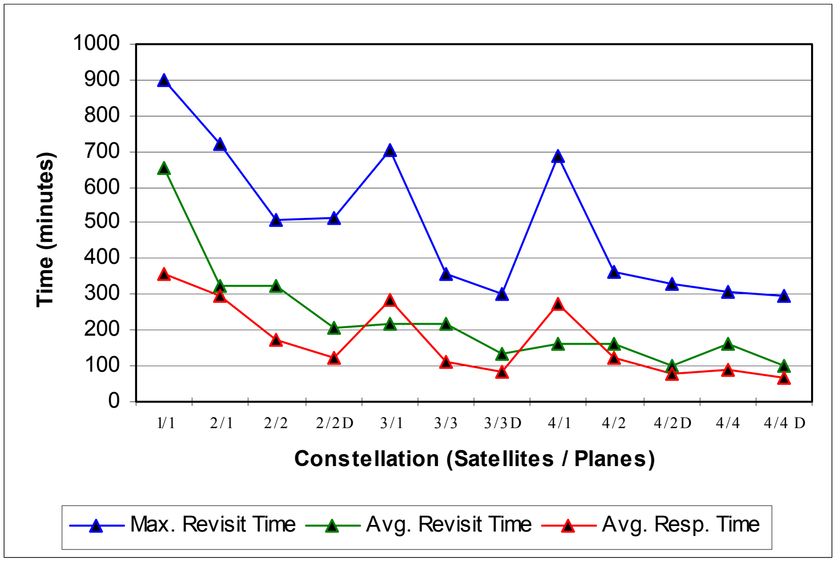

Figure 6. Canada East Coverage Performance.

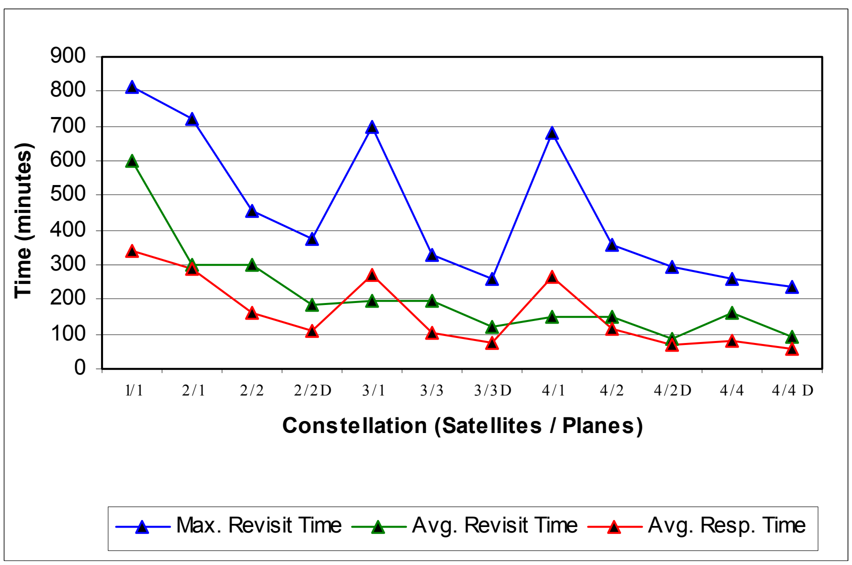

Figure 6. Canada – West: Coverage Performance.

The coverage performances obtained over the Canada East and West AOI are worse than those obtained over the Canada North AOI. This was expected due to the geographical locations of these target areas that extends between the latitudes 40°N to 60°N. The coverage performances of the constellation listed in Table 4 are illustrated in Table 5.

Table 5. Coverage performances over Canada East and West AOI.

Constellation	Avg Revisit Time (min.) East	Avg Revisit Time (min.) West	Max Revisit Time (min.) East	Max Revisit Time (min.) West	Avg Response Time (min.) East	Avg Response Time (min.) West
4/4D	101	90	297	236	68	60
4/2D	100	89	331	294	78	69
3/3D	136	121	299	259	83	77
2/2D	205	182	514	377	125	110

The graphs and figures above provide limited information as to the latitude dependency of the coverage performance. If the Canada East and West AOI results are compared to those of the Canada North AOI, the variability between the areas is clearly seen. However, within a specific AOI, that is not the case. In order to better illustrate this latitude dependency, Figure 7 shows the average revisit time within the three Canadian regions using the 4/4D constellation configuration.

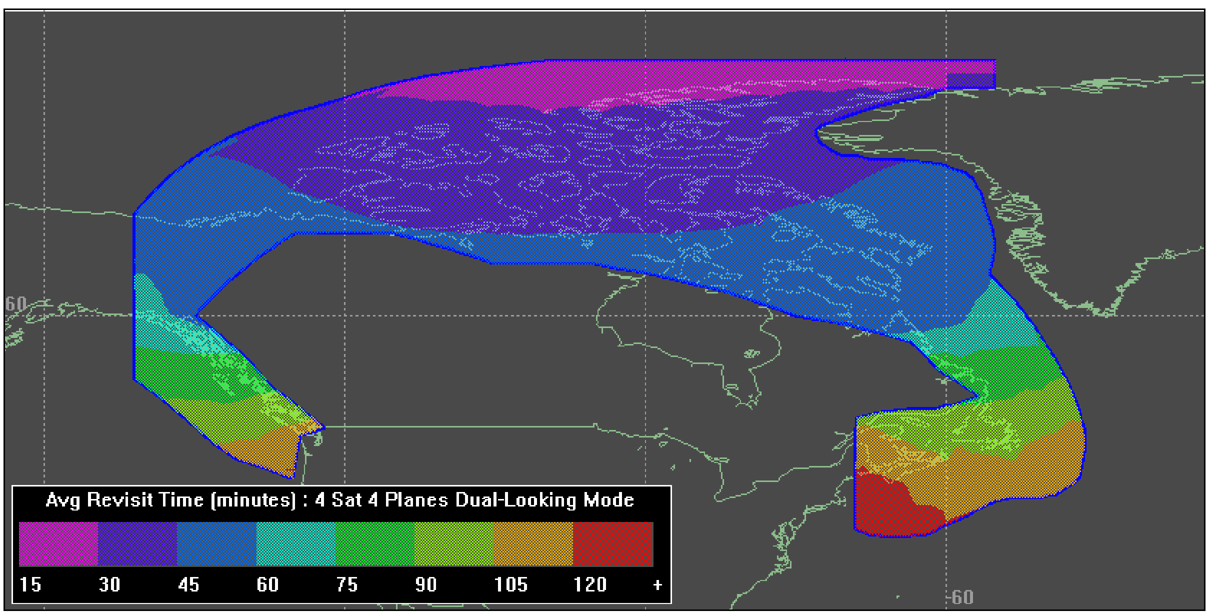

Figure 7. Canada AOI: Average Revisit Time versus Latitude.

4.1.2 Global Coverage Between Latitudes 60°N and 90°N

Figures 8 and 9 provide the coverage performances over the complete Northern hemisphere between latitudes 60°N and 90°N. It must be noted, that these figures represent the averages of 13 regions. In fact, STK divided this target area into 13 regions where 1 through 9 were located between latitudes 60°N and 75°N while regions 10 through 12 were located between 75°N and 90°N. Since the target area for this simulation was too large, the use of the dual-looking mode was not enabled.

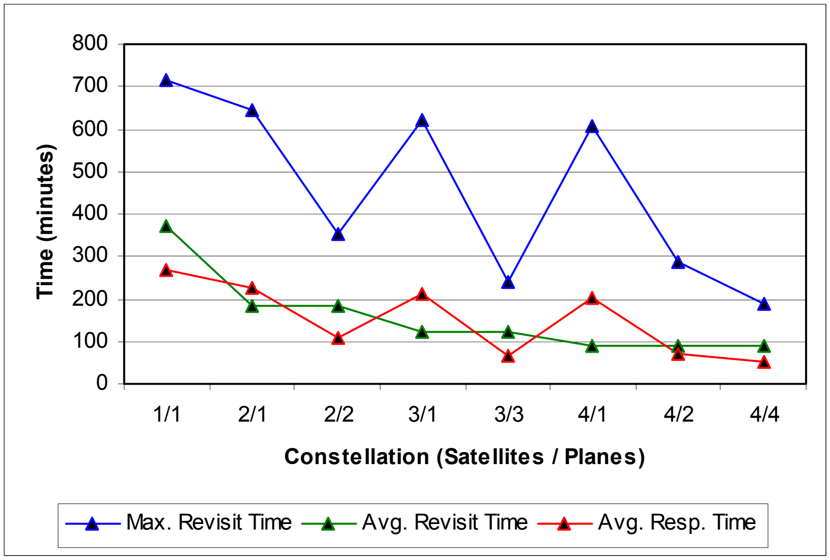

Figure 8. Northern hemisphere (60°N to 75°N): Coverage Performance.

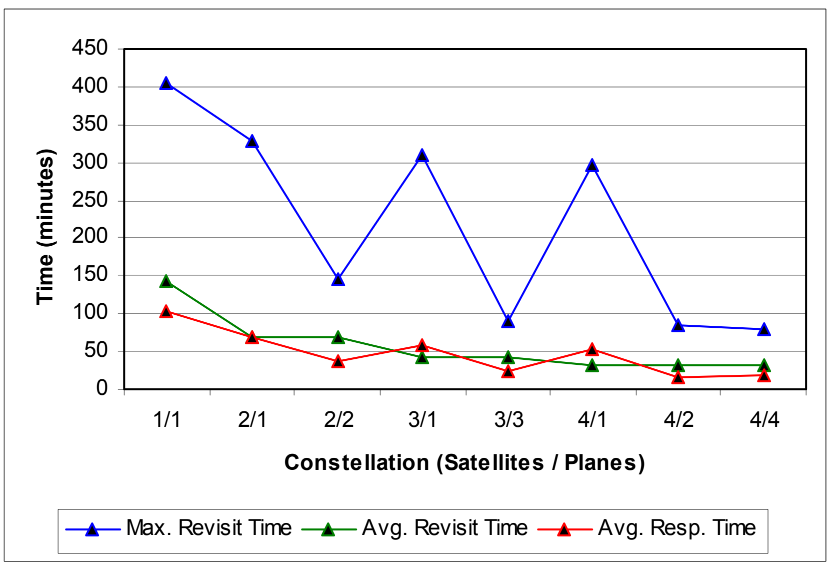

Figure 9 Northern hemisphere (75°N to 90°): Coverage Performance.

Again, the single plane constellations obtained the worst performances. Table 6 provide the coverage FOM for the four constellations with the best performances.

Table 6. Coverage performances over Latitudes 60°N to 90°N.

Constellation	Avg Revisit Time (min.)		Max Revisit Time (min.)		Avg Response Time (min.)	
	60° – 75°	75° – 90°	60° – 75°	75° – 90°	60° – 75°	75° – 90°
4/4	89	31	188	78	51	18
4/2	89	31	285	84	70	16
3/3	121	44	238	91	67	24
2/2	184	68	355	146	109	36

Figure 10 provides a view of how coverage performance varies as a function of latitude between latitudes 60°N and 90°N. The figure illustrates the average revisit time versus latitude using the 4/4 constellation configuration.

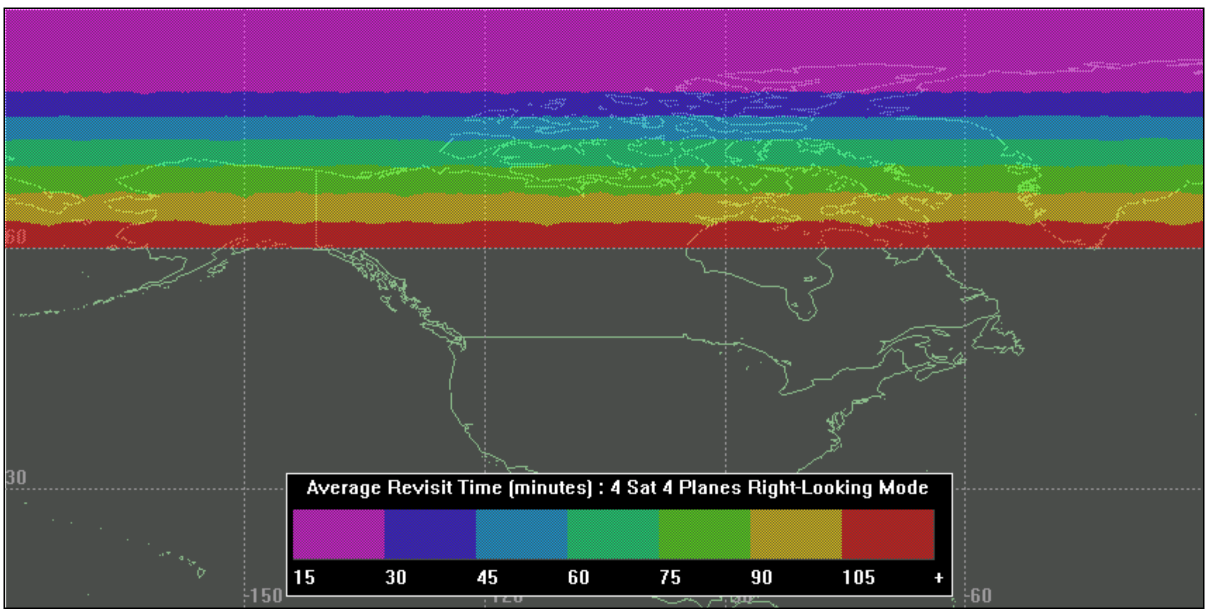

Figure 10. 60°N – 90°N AOI: Average Revisit Time versus Latitude.

4.1.3 Global Coverage Between Latitudes 60°N and 60°N

Figure 11 provides a rapid reference for comparing the performance of each constellation configuration tested during this simulation. Since the target area was so large the dual-looking mode was not enabled.

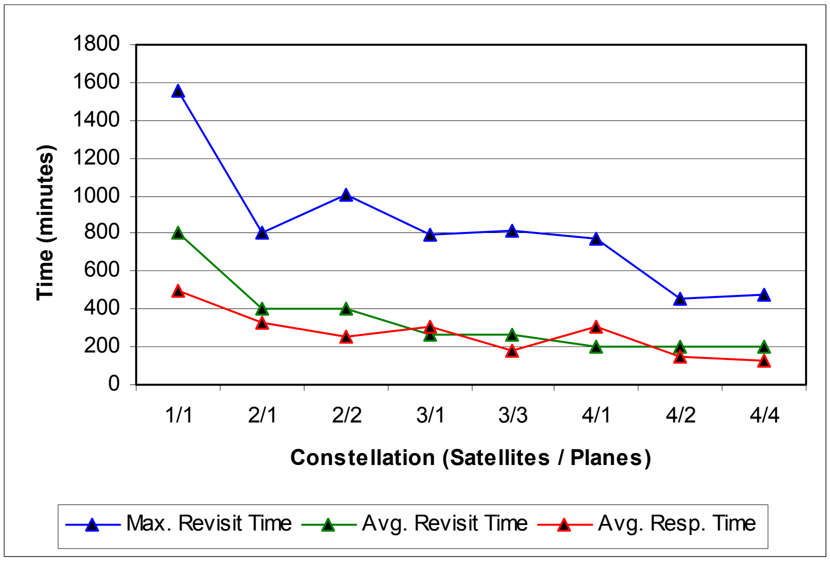

Figure 11. Latitudes 60°N to 60°N: Coverage performance.

Table 7 provide the coverage FOM for the four constellation configurations with the best performances.

Table 7. Constellation coverage performances over Latitudes 60°S to 60°N.

Constellation	Avg Revisit Time (min.)	Max Revisit Time (min.)	Avg Response Time (min.)
4/4	203	476	127
4/2	201	452	151
3/3	269	813	179
2/2	405	1005	255

As expected, as the number of satellites increases the coverage performance improves. Figure 12 illustrates the average revisit time variability as a function of latitude for a four-satellite in four planes constellation.

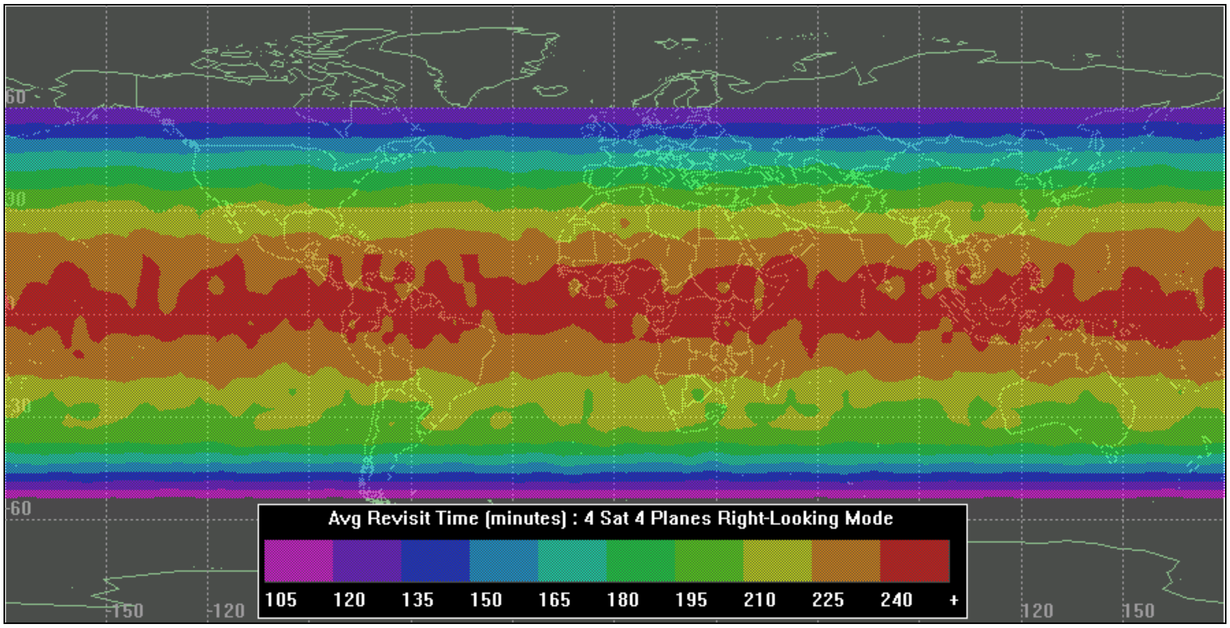

Figure 12. 60°S – 60°N AOI: Average revisit time versus latitude.

4.1.4 Areas of Interest: Persian Gulf and BiH

The results given above for 60°S to 60°N region provide a good idea as to the general coverage performance of the various constellation constellations, in a general wide-area surveillance mode when the dual-looking mode is not enabled. However, without the use of the dual-looking mode, the results are incomplete. An actual theatre of operations would be relatively small target area for a SBR and consequently, the dual-looking mode would be employed to improve the coverage obtained in the above scenario. Figures 13 and 14 as well as Tables 8 and 9 illustrate the coverage performance results that were obtained over the Persian Gulf and BiH AOI respectively, two regions over which the dual-looking mode was employed.

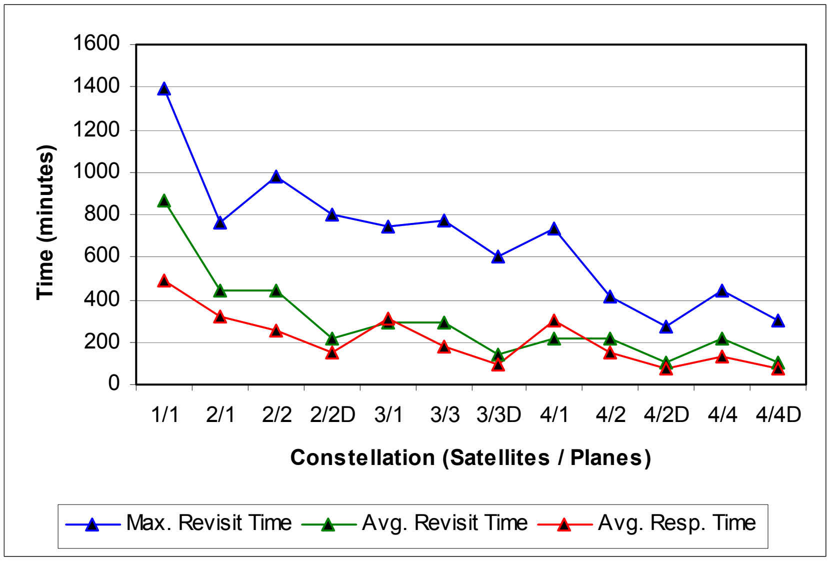

Figure 13. Persian Gulf AOI: Coverage performance.

Table 8. Coverage performances over Persian Gulf.

Constellation	Avg Revisit Time (min.)	Max Revisit Time (min.)	Avg Response Time (min.)
4/4D	106	301	73
4/2D	104	274	76
3/3D	141	599	96
2/2D	214	800	155

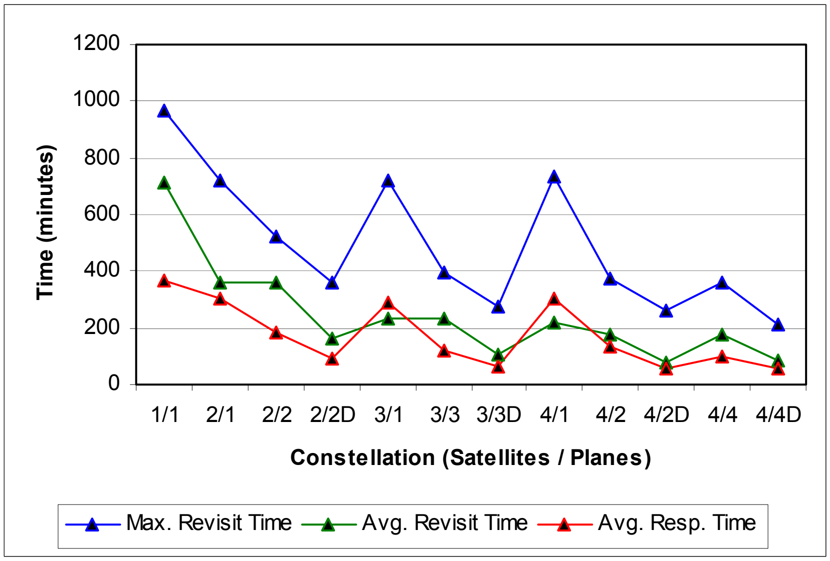

Figure 14. BiH AOI: Coverage performance.

Table 9. Coverage performances over BiH.

Constellation	Avg Revisit Time (min.)	Max Revisit Time (min.)	Avg Response Time (min.)
4/4D	82	212	57
4/2D	77	262	54
3/3D	104	277	66
2/2D	160	359	95

The graphical representations used in Figure 15 and 16 illustrate how the coverage varies with latitude within the AOI using the 4/4D constellation configuration.

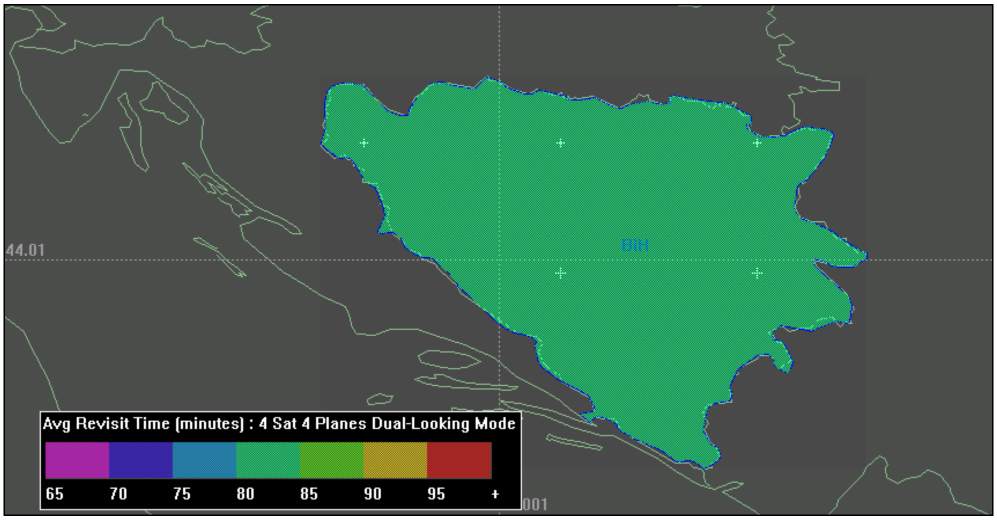

Figure 15. BiH AOI: Average Revisit Time versus Latitude.

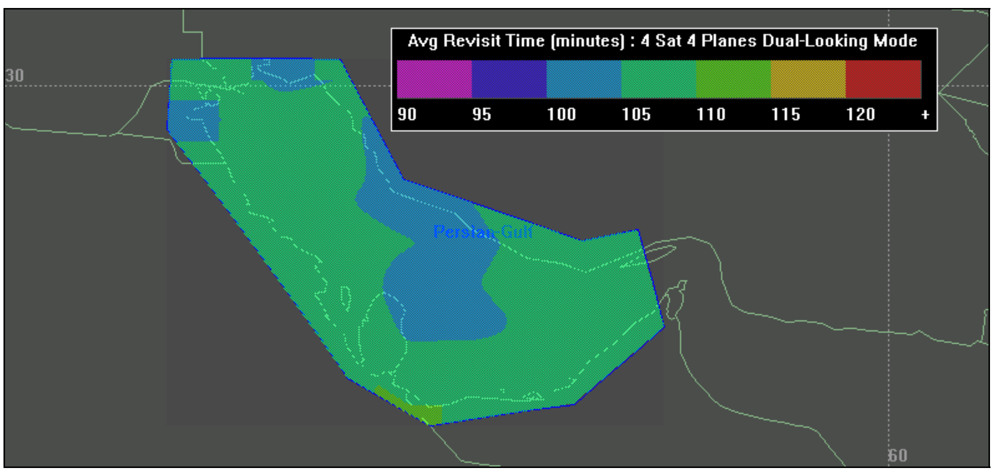

Figure 16. Persian Gulf AOI: Average Revisit Time versus Latitude.

4.2 Analysis of the results

The results obtained during this study have shown that a wide area surveillance SBR constellation consisting of two to four satellites could be militarily useful for a variety of missions. As a reminder, it was assumed that for a SBR surveillance system to be considered militarily useful as a stand alone system, an average revisit time lower than 60 minutes over the Canada North AOI would have to be obtained. This assumed mission requirement was met by three constellations, namely the 3/3D, 4/2D, and 4/4D configurations.

When considering the coverage performance obtained over the Canada East and West AOI for the three configurations mentioned above, average revisit times varied between approximately

90 to 140 minutes. These figures indicate that a limited SBR constellation would not be military useful as a stand-alone surveillance system over the eastern and western territorial waters. However, the results suggest that a SBR system could augment other sensors covering these regions such as the High Frequency Surface Wave Radar (HFSWR) or a fleet of manned or unmanned maritime patrol aircraft. Surveillance in the Canadian northern waters could be left mostly to the SBR system and when required, be augmented with other surveillance platforms when requirements demand lower revisit times to fill the gaps left from the satellites.

The second surveillance scenario modeled for which a future Canadian SBR constellation could be employed was the global wide area surveillance between 60°N and 90°N in augmentation to an allied SBR global surveillance system covering the lower latitudes between 60°S and 60°N. Average revisit times varied between approximately 90 to 120 minutes between latitudes 60°S and 75°N, the region of interest where the majority of moving targets are most likely to be located. Considering the amount of activity in this area, it is reasonable to assume that a limited SBR constellation could be sufficient for monitoring the northern hemisphere. It must be noted that enabling the dual-looking mode to target specific AOI will lower the average revisit times over these regions. In an unlikely situation where constant surveillance is required, airborne assets could then be employed to fill the coverage gaps.

In the context of augmenting an allied SBR global surveillance system covering the lower latitudes between 60°S and 60°N, the results for the average revisit times varied between 200 and 270 minutes. Although these results are not impressive when considered by themselves, a limited constellation of SBR as proposed in this study would still make a noteworthy contribution. First, the proposed Canadian constellation would be well suited to cover the latitudes above 60°N on a global scale as mentioned above. This would cover the gap left by an allied constellation covering the lower latitudes. Second, this limited constellation would also provide additional redundant coverage to an allied constellation from different orbits, effectively reducing the chance of lost targets due to terrain masking or unfavourable geometric effects. Third, a Canadian SBR constellation could ultimately allow allies participating in such a venture to lower the required number of spacecraft in their constellation to achieve the desired coverage. From a Canadian perspective, a contribution to a worldwide SBR surveillance system would undoubtedly provide DND access to a much larger system at a relatively lower cost.

In both of the global scenarios, the size of the AOI precluded the use of the dual-looking mode. However, as shown over the Persian Gulf and BiH AOI where this mode was enabled, average revisit times for the three constellation configurations ranged between 105 to 140 minutes over the Persian Gulf and between 80 and 104 minutes over BiH. The figures clearly demonstrate that a limited SBR constellation, as a sole surveillance system, can't be employed for tactical purposes. But, if employed to augment an existing ISR architecture consisting of ground-based and airborne sensors, tactical exploitation of a limited SBR constellation could become feasible. Accordingly, a SBR constellation could cue the other sensors in the ISR system whose coverage is restricted to only a portion of the whole region, allowing them to concentrate on the commander's critical information requirements.

4.3 Suggestions for Future Research

Now that it has been determined that a SBR SMTI constellation varying in number between two and four satellites has a potential military utility, future research should be conducted in order to further refine the concept and match it with requirements. Three main efforts of the next study should be, but not limited to:

- Clear enunciation of the DND surveillance requirement with respect to SBR.
- Optimization of the coverage through constellation optimization.
- Improved modeling of the SBR SMTI sensor and inclusion of the SAR sensor.

4.3.1 Surveillance Mission Requirements

For this study, it was assumed that the *raison d'être* of a future DND SBR SMTI system would be the wide area surveillance of the Northern Canadian territorial waters. It was also assumed that for a SBR to be considered military useful, average revisit times over that region would have to be lower than 60 minutes. These assumptions were based on an educated guess of future ISR requirements. Before further studies on the utility of a limited SBR constellation for DND are initiated, it is strongly recommended that the probable surveillance mission requirements of a future Canadian SBR surveillance system be clearly stated. By clearly defining how a SBR system would fit in a future national, and/or international, ISR architecture, future studies will then be focused towards the requirements which should ultimately lead to more pertinent results.

Once probable future surveillance requirements are stated, the other sensors of the ISR architecture within which the SBR constellation will operate should be modelled to provide an overview of how a SBR will augment the existing and planned sensors. Ultimately, this will allow for a more informed decision as to the true usefulness of a future SBR constellation. A better understanding of the mission requirements could also lead to the elaboration of possible concepts of operation for a DND SBR surveillance system.

4.3.2 Constellation Optimization

In this study, many of the constellation parameters were kept at a constant in order to limit the time spent on the study. Future work must also include constellation optimization as this will have a significant impact on not only the coverage performance but on the design of a number of key spacecraft subsystems parameters. Constellation design encompasses an extremely large trade space that includes orbital altitude and eccentricity, total number of satellites distributed in a number of orbital planes, and relative phasing between the satellites. STK proved to be an inefficient tool at optimizing the constellation optimization process. Any future constellation optimization research should seriously reconsider the usefulness of the STK software suite. Although there are no COTS software packages that can assist one in designing optimized constellations, the creation of an in-house program could be a worthwhile investment.

4.3.3 Improved Modelling of the SBR sensors

This study limited itself the total field of view of the electronic steered array antenna in a SMTI mode. More precisely, the model reproduced the scan frame within which the SMTI radar beam will scan for moving target. Although the SMTI sensor should continue to drive the coverage optimization process, further studies should most certainly include coverage performances of the SAR sensor, as it will be an important contributing sensor to a SBR spacecraft.

This first study modelled a dual-looking mode on the SBR SMTI/SAR satellite, however it was very rudimentary in nature. Once the probable surveillance requirements of a future Canadian SBR surveillance system are clearly stated, the following studies should remodel the dual-looking mode to take under account these requirements. STK has shown severe limitations with respect to this particular criterion. If a dual-looking mode can't be integrated efficiently in the STK simulations, then the use of other software suites to simulate SBR should be seriously considered.

5. Conclusion

The aim of this study was to quantify the coverage performances that can be obtained from a constellation of SBR satellites, varying in number between one and four spacecraft, each equipped with a SMTI sensor. The coverage performance for this study was evaluated based on revisit and response times obtained over selected AOI and not on performance as a function of detection, tracking, and identification of discrete surface moving targets. The results of this study will contribute in determining the military utility of a limited SBR constellation intended for the wide-area surveillance of ground and maritime targets for DND.

The results indicate that a constellation consisting of two to four SBR satellites could be militarily useful to the CF for the surveillance over the Canadian northern territorial waters where current coverage is very limited. As for coverage over the Eastern and Western territorial waters, the SBR constellation would prove useful, but due to the lower coverage performance, the system should not replace existing surveillance systems but augment them to provide increased coverage. In this case, the SBR surveillance system could be used to augment current ground based and airborne surveillance sensors such as the HFSW radar or the maritime search radar on board the maritime patrol aircraft. In the context of support to CF elements deployed overseas it is not unreasonable to assume that the proposed SBR system could be employed for tactical purposes if used within a larger ISR system.

In the context of augmenting an allied SBR global surveillance system covering the lower latitudes between 60°S and 60°N, the proposed Canadian constellation would be well suited to cover the latitudes above 60°N on a global scale. As well, this limited constellation could provide additional redundant coverage to the allied constellation from different orbits, effectively reducing the chance of lost targets and most probably, lowering the total number of spacecraft required in the allied SBR constellation. From a Canadian perspective, a contribution to a worldwide SBR surveillance system would undoubtedly provide DND access to a much larger system at a relatively lower cost.

Now that it has been determined that a SBR SMTI constellation varying in number between two and four satellites has a potentially useful military utility, future work on the SBR military utility study should be continued in order to obtain more accurate information as to the true usefulness of a limited SBR SMTI constellation. The next study should consists at least of the following three main efforts:

- Clear enunciation of the DND surveillance requirement with respect to SBR.
- Optimization of the coverage through constellation optimization.
- Improved modelling of the SBR SMTI sensor and inclusion of the SAR sensor.

6. References

1. Martins-Camelo, L., Gaudette, Y., Cyr, J.-M., Gavrilovic, M., Moss, R., Rufenacht, H., Brand, A., Edward, I. EMS Technologies Ltd. (2003). Space-Based GMTI/SAR System Study – Phase C. DRDC Ottawa Contract Report CR 2003-026.

2. Wertz, J.R. (2002). Orbit and Constellation Design, Space Mission Analysis and Design, 3rd Ed. Kluwer Academic Publisher.

Annex A – STK Seed Satellite Orbital Parameters

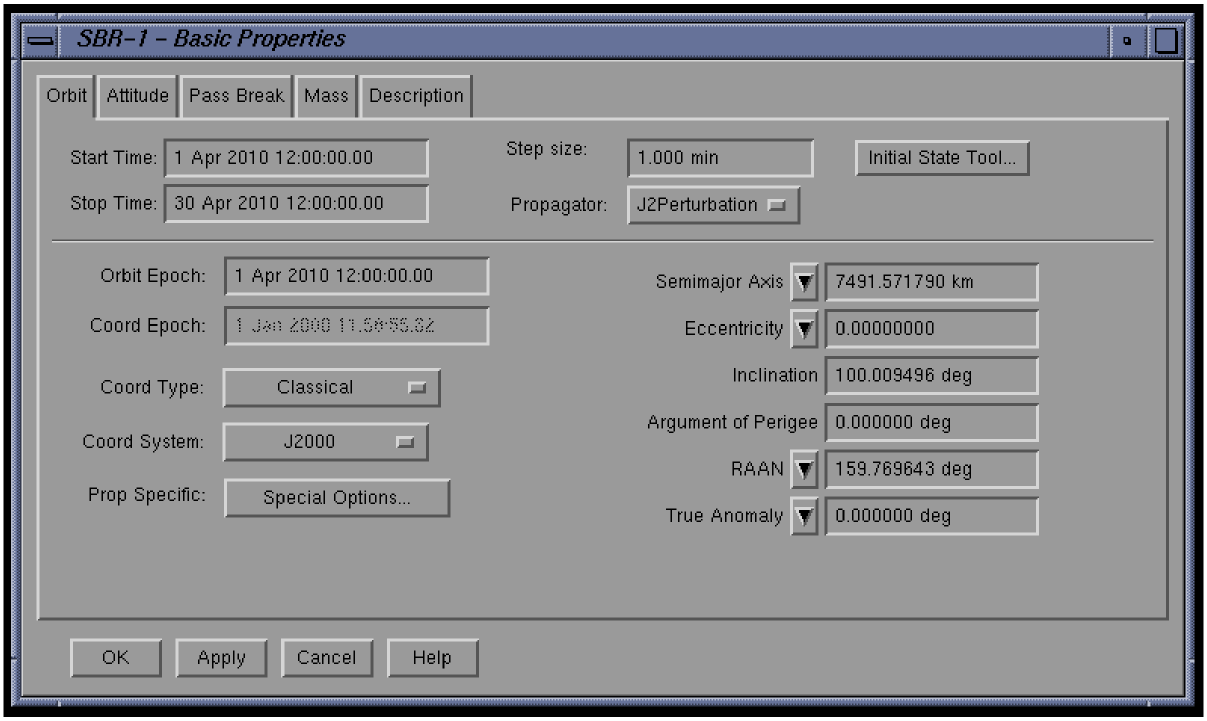

Figure 17. STK Seed satellite orbital parameters.

Annex B – STK Parameters of the SMTI Sensor

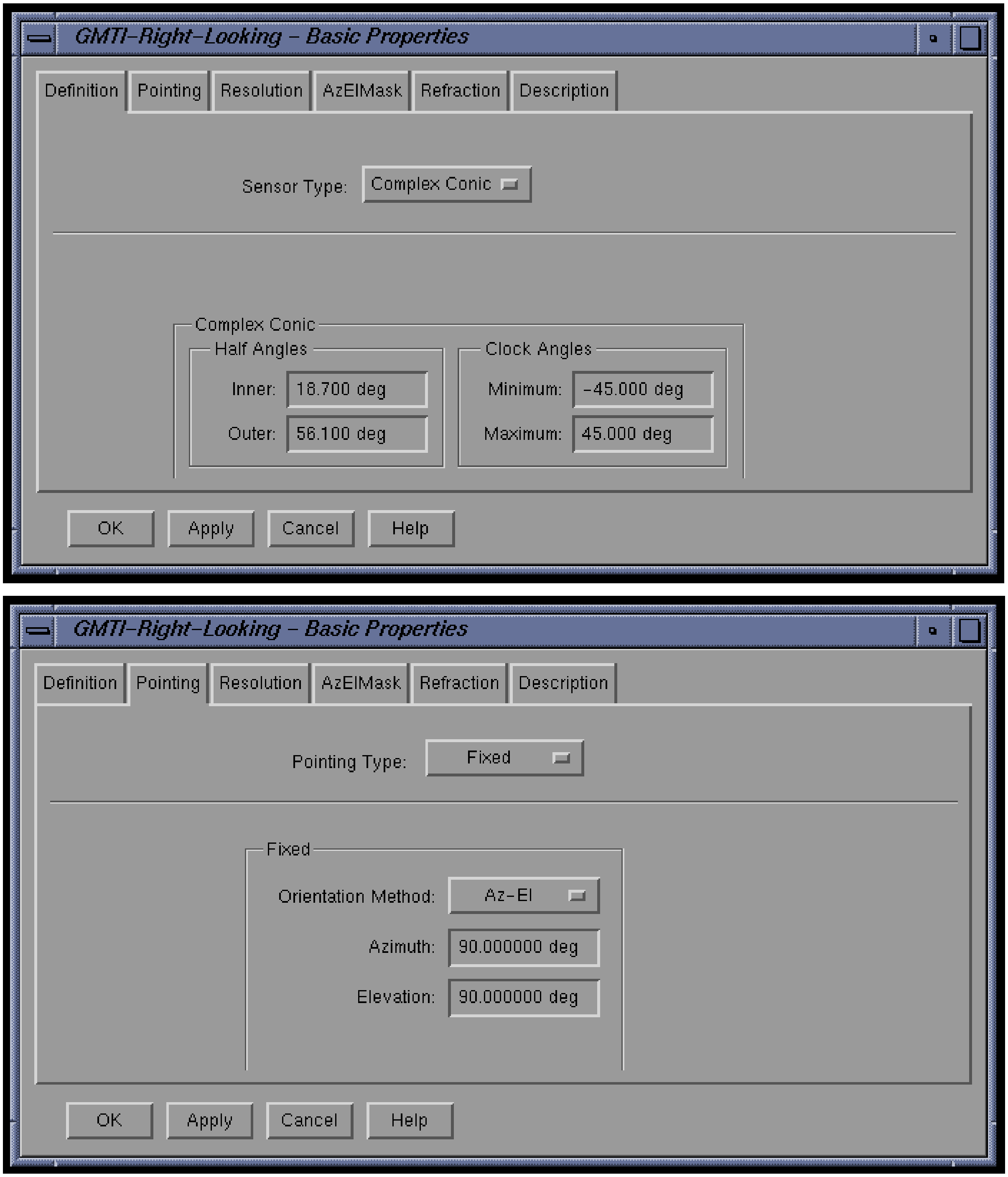

Figure 18. STK Parameters of the SMTI sensor.

List of symbols/abbreviations/acronyms/initialisms

AOI	Area of Interest
BiH	Bosnia i Herzegovina
CF	Canadian Forces
COTS	Commercial Off The Shelf
DND	Department of National Defence
GMTI	Ground Moving Target Indication
IFOV	Instantaneous Field of View
SAR	Synthetic Aperture Radar
SBR	Space-Based Radar
SMTI	Surface Moving Target Indication
STK	Satellite Tool Kit

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The primary objective of this study is to assess the potential military utility of a limited Space-Based Radar (SBR) constellation for the wide-area surveillance of ground and maritime targets for the Department of National Defence (DND). As a result, it quantified the coverage performances of a limited number of SBR constellations, varying in number between one and four spacecraft, each equipped with a Surface Moving Target Indicator (SMTI) sensor. Constellation coverage performances in this case were evaluated based on revisit and response times obtained over selected areas of interest (AOI) and not performance as a function of detection, tracking, and identification of discrete surface moving targets. Satellite Tool Kit, a commercially available software suite that performs satellite performance analysis, was used to perform surveillance simulations and to produce the coverage results described in this report. The SMTI sensor parameters were obtained from specifications provided by Dr. C.E. Livingstone of DRDC Ottawa and from contract reports produced by EMS Technologies Canada, Ltd under the Space Based SMTI/SAR Systems Study. Three scenarios were used to evaluate the military potential of the simulated SBR constellations. The first considered a wide-area surveillance mission over the Canadian territorial waters with a specific interest in the surveillance of northern Canada. The next two scenarios considered a limited Canadian SBR constellation being used to augment an allied SBR constellation covering the latitudes between 60oS and 60oN. Accordingly, the second scenario considered a wide-area surveillance mission between latitudes 60o to 90oN while the third considered a wide-area surveillance mission between latitudes 60oS and 60oN. The results from this study indicate that a constellation consisting of two to four SBR satellites polar orbiting satellites could be military useful to DND for the surveillance over the Canadian territorial waters. The results also demonstrated that this same surveillance system could also be employed in augmentation to national or allied surveillance sensors in a much wider intelligence, surveillance and reconnaissance (ISR) architecture.

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Space-Based Radar, satellite constellations, military utility

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