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Canadian space-based radar surveillance constellation implementation concepts

Chuck Livingstone

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Abstract

With the advent of the Canadian RADARSAT Constellation Mission, the Canadian Space Agency has embarked on a transition from the use of individual radar surveillance satellites, represented by RADARSAT-1 and RADARSAT-2, to the use of a radar satellite constellation to perform radar surveillance observations. The transition from single satellites to satellite constellations drives some major changes in the way in which space-based surveillance radars are developed and operated and some equally major changes in the way in which surveillance measurements are tasked, retrieved and used. The use of constellations of radar surveillance satellites is a completely new way of doing business and raises many issues that will need to be addressed. This document presents the author's opinion on many of the issues that will need to be addressed as Canada evolves its surveillance capabilities and makes suggestions about work that will be required if one (or more) constellation(s) of Canadian spacecraft is a viable, long-term surveillance solution.

This note is written as a discussion paper that presents a vision of a possible way for Canada to develop and use a space-based surveillance radar constellation to provide a straw-man starting point for concept development and implementation. It is intended to trigger discussions about the development and implementation of Canadian Government space-based surveillance resources and their uses.

Résumé

Avec l'avènement de la mission canadienne de la Constellation RADARSAT, l'Agence spatiale canadienne a entrepris une transition pour passer de l'utilisation de satellites individuels de surveillance radar, représentés par RADARSAT-1 et RADARSAT-2, à l'utilisation d'une constellation de satellites radar pour effectuer des observations de surveillance radar. Le passage des satellites simples aux constellations de satellites provoque des changements importants dans la façon de concevoir et d'utiliser les radars de surveillance à partir de l'espace et des changements tout aussi importants dans la façon de demander, de récupérer et d'utiliser des mesures de surveillance. L'utilisation des constellations de satellites de surveillance radar est une méthode de fonctionnement complètement novatrice et soulève de nombreuses questions qui devront être examinées. Dans le présent document, l'auteur donne son avis sur nombre de questions à examiner au fur et à mesure que le Canada développe ses capacités de surveillance. Il formule aussi des suggestions sur les travaux qui seront nécessaires si une ou plusieurs constellations d'engins spatiaux canadiens sont une solution de surveillance viable et à long terme.

La présente note constitue un document de travail et présente une vision d'une façon possible pour le Canada de développer et d'utiliser une constellation de radars de surveillance à partir de l'espace pour fournir un point de départ à un document d'orientation sur le développement et l'application d'un concept. Le présent document vise à déclencher des discussions sur le développement, l'application et l'utilisation de ressources de surveillance à partir de l'espace du gouvernement du Canada.

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Executive summary

Canadian space-based radar surveillance constellation implementation concepts

Chuck Livingstone; DRDC Ottawa TN 2012-013; Defence R&D Canada – Ottawa; May 2012.

Introduction or background: In 2005 Canada introduced the concept of using a constellation of surveillance radar satellites to replace the single satellite observation model represented by RADARSAT-1 and RADARSAT-2. The RADARSAT Constellation Mission (RCM) design is based on Government of Canada surveillance requirements as defined by representatives from several government departments and is primarily driven by Environment Canada CIS (Canadian Ice Service) ice monitoring requirements and by DND wide-area ship monitoring requirements. The individual RCM satellites are less capable than RADARSAT-2, and the RCM constellation design has been driven by wide area coverage but lacks some of the more advanced capabilities of RADARSAT-2. The RCM will be a government-owned surveillance resource. Satellite design is currently proceeding to the detailed design phase with launch scheduled for end of the RADARSAT-2 design life in 2016. In September 2010, a study contract RFP (request for proposal) was issued by CSA (Canadian Space Agency) to define options for an expansion to the RCM constellation to increase the constellation size using more capable satellites.

With the development of RCM, Canada is changing its space-based radar surveillance model from individual satellite surveillance tools to a constellation of surveillance satellites. This is a fundamental change in and has a number of long term implications for Canadian surveillance capability.

Results: The use of Canadian-developed radar satellite constellations is examined in the context of the available international sensors and the author's views on issues surrounding the development of indigenous systems are presented. A model for a Canadian constellation of radar surveillance satellites is outlined and its components are discussed in general and in the context of a high-level straw-man design.

Significance: Although Canada is embarking on the development of a constellation of radar satellites (RCM) to fill some identified national surveillance requirements, there has been little thought about the longer-term implications of this action. The idea of a constellation as a long-lived surveillance entity whose evolution is driven by national surveillance requirements is proposed and many of its implications are examined to provide an initial set of concepts for DND "ways forward" considerations. A number of DND and Canadian government policies and processes are identified for discussion and possible change.

Future plans: The topics presented in this document identify starting points for multi-year activities that will need to happen if the Government of Canada and DND, specifically, hope to get the best possible value from investments in surveillance satellite constellations.

Sommaire

Canadian space-based radar surveillance constellation implementation concepts

Chuck Livingstone; DRDC Ottawa TN 2012-013; R & D pour la défense Canada – Ottawa; mai 2012.

Introduction ou contexte: Avec l'avènement de la mission canadienne de la Constellation RADARSAT, l'Agence spatiale canadienne a entrepris une transition pour passer de l'utilisation de satellites individuels de surveillance radar, représentés par RADARSAT-1 et RADARSAT-2, à l'utilisation d'une constellation de satellites radar pour effectuer des observations de surveillance radar. Le passage des satellites simples aux constellations de satellites provoque des changements importants dans la façon de concevoir et d'utiliser les radars de surveillance à partir de l'espace et des changements tout aussi importants dans la façon de demander, de récupérer et d'utiliser des mesures de surveillance. L'utilisation des constellations de satellites de surveillance radar est une méthode de fonctionnement complètement novatrice et soulève de nombreuses questions qui devront être examinées. Dans le présent document, l'auteur donne son avis sur nombre de questions à examiner au fur et à mesure que le Canada développe ses capacités de surveillance. Il formule aussi des suggestions sur les travaux qui seront nécessaires si une ou plusieurs constellations d'engins spatiaux canadiens sont une solution de surveillance viable et à long terme.

La présente note constitue un document de travail et présente une vision d'une façon possible pour le Canada de développer et d'utiliser une constellation de radars de surveillance à partir de l'espace pour fournir un point de départ à un document d'orientation sur le développement et l'application d'un concept. Le présent document vise à déclencher des discussions sur le développement, l'application et l'utilisation de ressources de surveillance à partir de l'espace du gouvernement du Canada.

Résultats: L'utilisation de constellations canadiennes de satellites radar est examinée en fonction des capteurs internationaux disponibles, et l'avis de l'auteur sur les questions relatives au développement de systèmes locaux est présenté. Un modèle de constellation canadienne de satellites de surveillance radar est décrit et ses composants sont examinés de manière générale et dans le contexte d'un concept d'orientation de haut niveau.

Importance: Bien que le Canada entreprenne le développement d'une constellation de satellites radar (MCR) pour répondre à certains des besoins établis de surveillance nationale, peu de temps a été accordé à l'étude des conséquences à long terme de cette action. L'idée d'une constellation comme entité de surveillance de longue durée dont l'évolution dépend des besoins de surveillance nationaux est proposée, et nombre de ses conséquences sont examinées pour fournir un ensemble initial de concepts aux fins de considérations des « voies à suivre » du MDN. Divers processus et politiques du MDN et du gouvernement du Canada sont en outre mentionnés aux fins de discussion et de modification possible.

Perspectives: Les sujets indiqués dans le présent document constituent des points de départ pour les activités pluriannuelles qui devront avoir lieu si le gouvernement du Canada et le MDN espèrent, notamment, maximiser le rendement des investissements dans les constellations de satellites de surveillance.

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1 Introduction

Land and maritime surveillance activities needed to support DND's mandate require a broad range of sensors, platforms and information extraction systems that provide compatible, evolving information streams over long periods of time. Surveillance observations are required for national and global areas of interest (AOIs) that vary in size from a few square kilometres to millions of square kilometres, over time intervals that vary from hours to decades, at resolutions that vary from fractional square metres to square kilometres, and repeat periods that vary from minutes to days. At the present time DND's surveillance capabilities are incomplete, fragmented and in many cases mutually incompatible [1]. The problem of growing, focusing, integrating and managing the aggregate system of capabilities is far reaching and is beyond the scope of this report.

This document looks at the space-based radar surveillance sub-set of systems designed to address specific DND surveillance requirements in the context of its broader surveillance requirements and within the context of Canadian whole-of-government surveillance needs. Other Canadian surveillance issues such as: defining and managing observation persistence, defining and enabling mixtures of observation measurement types and platforms for specific surveillance problems, and integrating information from multiple sources into requirements-driven information sets are necessarily dealt with elsewhere.

At present, Canadian Government surveillance needs and implementation strategies are contained within multiple departmental silos [2]. This note is written as a discussion paper that presents the author's vision of a way for Canada to develop and use a space-based surveillance radar constellation. Although it is written from a DND perspective, it is intended to trigger discussions about the development and implementation of Canadian Government space-based surveillance resources and their uses.

1.1 Space-based radar surveillance

Imaging space-based surveillance radars can, in principle, provide spatial, temporal, structural and motion information for defined AOIs in all weather conditions at any time of day. Orbit properties define the ability to exactly repeat observations at periodic intervals of many days for any single sensor so that changes in observations between these exact repeats represent changes in the observed terrain contents (for well-calibrated instruments). Small sensor position offsets between repeat observation conditions allow the creation of interferometric terrain elevation maps from coherent SAR (Synthetic Aperture Radar) data. The observation repeat interval for coherent observations needed to form interferometric images or coherent change detections depends on the satellite orbit design, the number of identical satellites that are on orbit and which orbits have been selected.

Modern space-based surveillance radars are predominantly synthetic aperture imaging instruments (i.e., SARs) that have a set of observation modes that can be programmed on orbit. Each instrument can be set up for any one of a large number of observation properties that can be reconfigured for different surveillance tasks within an orbit. Each configuration defines an operating mode, and the modes are mutually exclusive for any observation.

Radars measure the physical structure of an observed area as the summed, coherent, radar returns from every physical object (dielectric structure) within a radar resolution cell that is spatially larger than approximately 1/10 of the radar wavelength (smaller objects also contribute reflected signals but very weakly). The position, dielectric constant and physical dimensions of each terrain element within a radar resolution cell determines the contribution of that element to the radar return within the cell and thus to the brightness of the dot that is the resolution cell image. For surveillance applications the choice of resolution cell size needed to observe desired terrain features depends on the physical dimensions of the smallest feature to be observed. Where feature (target) shape information is required, many resolution cells (the size of many depends on the detail required) must be contained within the physical dimensions of the target. Because of data sampling rate considerations and volume limitations, the finer the radar resolution selected, the smaller the observable observation swath.

Radars are not sensitive to the chemistry (colour) of terrain elements and are only weakly sensitive to other chemical properties (for vegetation, radars are sensitive to the presence of free and bound water). Where surveillance requirements include the observation of colour and thermal information other sensor types must be used.

1.2 Canadian space-based radar surveillance experience

With the launch of RADARSAT-1 in November 1995, Canada embarked on the development of a national space-based radar surveillance capability. RADARSAT-1 was defined as an earth observation satellite whose SAR imaging capabilities were defined by natural resources, sea ice and large scale cultural (agriculture) requirements. Remote sensing research using RADARSAT-1 and airborne SAR systems developed information extraction algorithms and procedures for a large number of applications areas. The experimental coarse resolution, wide swath ScanSAR mode implemented in RADARSAT-1 formed the basis for ongoing operational sea ice surveillance by the Canadian Ice Service (CIS). Site and time specific surveillance missions to monitor natural disaster events and international crisis events have been developed and executed. Ocean surveillance applications to provide wind field data to meteorological models were developed.

RADARSAT-2, launched in December 2007, expanded the observation capability of RADARSAT-1 to include new modes and measurement capabilities (polarimetry, ground moving target indication (GMTI) and finer resolution). The RADARSAT-2 design was based on research results that used RADASAT-1 and airborne research radar measurements to explore expanded instrument capability. The operational sea-ice surveillance and on-going ocean surveillance activities were part of the design and the DND-sponsored GMTI mode was developed as an experimental capability. RADARSAT-2 also was used to explore the role of a commercially owned and operated system to provide both national and commercial imaging capability.

In 2005, Canada introduced the concept of using a constellation of surveillance radar satellites to replace the single satellite observation model represented by RADARSAT-1 and RADARSAT-2. The RADARSAT Constellation Mission (RCM) design is based on Government of Canada (GoC) surveillance requirements as defined by representatives from several government departments and is primarily driven by CIS ice monitoring requirements and by DND wide-area ship monitoring requirements. The RCM satellites are less capable than RADARSAT-2 and the constellation design has been driven by wide area coverage. The RCM will be a government-owned surveillance resource. Satellite design is currently proceeding to the detailed design phase with launch scheduled for end of the RADARSAT-2 design life in 2016. In September 2010, a study contract RFP (request for proposal) was issued by CSA to define options for an expansion to the RCM constellation. MDA (McDonald, Dettwiler and Associates) and Astrium Infoterra won contracts to do initial options analysis and high level definition for the RADARSAT Next Generation (RNG) constellation based on the draft DND surveillance requirements outlined in Annex A. The studies, including evaluations of requirements extension provided by other government departments, are due for completion by March 2012.

1.3 Vision

With the CSA (Canadian Space Agency) development of RCM and its RNG extension, Canada is changing its space-based radar surveillance model from individual satellite surveillance tools to a constellation of surveillance satellites. While there is no written policy statement that this is a considered change to the Canadian approach to space-based surveillance, other nations (Germany and Italy) are following similar development programs. The move from single, unique surveillance satellites to constellations of surveillance satellites is a fundamental change in surveillance implementation, and has a number of long term implications for Canadian surveillance capability. In this document, we will assume a planned constellation lifetime of at least 20 years so that cost and performance efficiencies can be realized.

1. The service life of a constellation is much longer than the life of any single satellite contained in it. This defines a sustainment requirement.
2. The surveillance measurement capabilities of a constellation can exceed the measurement capabilities of any satellite within the constellation. This implies constellation augmentation requirements: to provide temporal resolution (revisit frequency) enhancements and to include multi-parameter observations that require more than one satellite type in the constellation.
3. The missions executed by a constellation can mature and evolve by evolving the properties of the satellites in the constellation and by evolving the constellation orbit properties. This implies a spiral development requirement. This also implies a continued evolution of the mission requirements to be executed.
4. The control and use of multiple satellites is more complex than the control and use of a single satellite. The initial implementation of Canadian and international surveillance constellations is based on the individual control of each satellite in the constellation. The growth and sustainment of the surveillance constellation paradigm implies a revision to the design of satellite control and receiving stations that treats the constellation as a surveillance entity and may promote the evolution of autonomous control functions.
5. The use of a constellation of satellites to provide surveillance capability implies that the satellite unit costs are reduced to make the process affordable. This, in turn, implies the existence of an R&D program that is aimed at sensor performance enhancement and production cost reduction.

To successfully implement a surveillance-constellation model for a planned lifetime of 20+ years:

1. A constellation program needs to be defined that executes satellite build and launch functions as a continuing stream as opposed to the current, sporadic major project activities.
    a. This implies the creation of design, production integration and test facilities that can be continually upgraded and replace the current practice of having “one-of” facilities that are rebuilt for each project in the one-satellite model.
    b. It implies the creation of highly automated information extraction services that are designed to create responsive and useful information streams from large

volumes of raw measurement data and to seamlessly disseminate information outputs to users in a timely manner.
   c. It also implies changes to the Canadian Government funding approval and contracting processes to shift from a discrete unit, project based model to a continuous-flow, program-based model.
2. An innovative research and development culture that contains active elements from academia, industry and government laboratories needs to be created and nurtured.
3. A forward-looking Canadian Government surveillance requirements development and review process needs to be implemented.
4. Policies that address the evolving roles of industry, government and international partners need to be developed and maintained.
5. International partners who have space-based surveillance assets need to be approached to identify opportunities for responsive information sharing and the appropriate international agreements need to be developed.

As the development of the RCM satellites is proceeding towards launch in 2016, work to define the properties of the next-generation of space-based radar sensors that will augment and expand the constellation is in progress.

1.4 Canadian data policy

The use of surveillance data from Canadian space-based systems is governed by the Remote Sensing Space Systems Act (RSSSA), 2005 [3]. This legislation sets out the principles that govern access to Canadian space-based surveillance data, the access control process and the ministerial responsibilities for interpreting and implementing the act. The Department of Foreign Affairs and International Trade (DFAIT) has the prime responsibility to control the administration of the act and to manage the regulatory structure.

As a persistent Canadian space-based surveillance system evolves, access to information from this system should evolve to maximize the benefit that Canadians obtain from the space surveillance system while protecting Canada's interests internationally. The Canadian data policy and its implementation under the RSSSA should evolve with, and be linked to, Canadian space-based surveillance system development.

2 Canadian government land, sea and navigable waterways surveillance requirements

Historically, formal surveillance requirements have lagged information provision capability since they have been based on current problems and tempered by proven technology. To shorten the time lags between the identification of critical surveillance requirements and the realization of the corresponding surveillance capability, requirements definition needs to be an evolving, future-focused process such as the one now in progress within DND. The requirement sets for evolving national programs are expected to shift over time as both technology and national needs evolve and must be tracked by a continually evolving delivery strategy. Planning for future systems requires that future needs are anticipated to guide development directions.

Some subset of the Canadian Government surveillance requirements can be satisfied by space-based observation systems or by a combination of space-based and either terrestrial or airborne systems. Given the development lead times for systems of this type, it is important that they are designed to respond to surveillance requirements that are predicted to be significant over their service life. Draft surveillance requirements developed by DND are captured in Annex A to provide an example set of forward-looking requirements that will influence the development and use of Canadian surveillance constellations.

This discussion looks at the space-based elements in a requirements-driven surveillance constellation context.

2.1 Stated requirements

Many Canadian government departments have developed and officially approved sets of surveillance requirements that are specific to their mandates. There is no process in place at the present time to consistently consolidate these disparate sets into a Government of Canada (GoC) surveillance requirement set.

2.1.1 Coastal and ocean surveillance

- DND has a presently defined requirement to detect and monitor the position, heading and speed of all ships whose length is greater than 25 m that are approaching within 1200 nautical miles of the Canadian coast [4].
- Environment Canada has a defined requirement to map sea ice cover and iceberg positions on all Canadian coasts [5].
- Environment Canada has a defined requirement to monitor meteorological conditions over Canada and its surrounding waters [2].
- The Department of Fisheries and Oceans has a defined requirement to monitor fishing activities in the Canadian economic zone [6].
- The Department of Fisheries and Oceans has a defined requirement to monitor oceanographic conditions off Canada's coasts [7].
- The Department of Fisheries and Oceans (Coast Guard) has a defined requirement for marine safety in all Canadian waterways [8].

2.1.2 Arctic surveillance

- DND has a defined requirement to monitor arctic activities that impact on Canadian sovereignty [4].
- DND has a defined requirement to provide search and rescue support in the Arctic [9].
- Environment Canada has a defined requirement to monitor sea ice cover along navigable arctic channels [10].
- The Department of Fisheries and Oceans has a defined requirement to provide ice navigation support and rescue in Arctic and other ice-infested waterways [10].
- Transport Canada has a defined requirement to regulate Arctic shipping safety [11].

2.1.3 Surveillance and monitoring of the Canadian land mass

- DND has a presently defined requirement to provide search and rescue support over the Canadian land mass and coastal regions [9].
- A number of Canadian Government departments and Provincial governments have mandates to monitor large scale cultural activities (agriculture, forestry, and shipping) and natural events over the Canadian land mass [2].

2.1.4 Surveillance in support of deployed government agencies

- DND has a requirement to provide surveillance and reconnaissance support for deployed land and naval forces at multiple spatial and temporal scales [12].

2.1.5 Surveillance in support of national allies

- Through NORAD, DND has a requirement to collaborate in monitoring all marine approaches to North America [13].
- Through NORAD, DND has a requirement to collaborate in monitoring air and space assets approaching and observing North America [13].

2.2 Earth-surface surveillance requirements evolution

Prior to the Terra-SAR-X launch in 2007, on-orbit, non-military, space-based radar surveillance system designs were focused on monitoring natural processes and resources that are measurable at scales of 20 m or larger. Surveillance requirements for both natural phenomena and cultural activities were defined for the accessible observation scales. Since 2007, a number of commercially accessible systems have been launched with resolutions and measurement functions that enable the monitoring of cultural activities at scales suitable for the observation of individual vehicles and urban infra-structure. Research into phenomena that are revealed by the enhanced observation capability will spawn (and is spawning) surveillance requirements that exploit the available information. The current Canadian Government requirements sets are largely based on the older, pre-2007 commercial satellite, observation capability limits.

Canadian Government surveillance requirements for cultural activities have not been clearly defined at this time (DND has developed draft requirements that cover some cultural surveillance activities) but some will evolve from current research into SAR polarimetry (target class identification), coherent change detection and SAR ground moving target indication (GMTI) vehicle motion measurements.

Except for high arctic regions observed by polar orbiting satellites, most existing space-based radar observations enable temporal observation granularity of one or two observations per day for any 30 km x 30 km region. This is certainly adequate for the vast majority of natural events monitoring application (except for marine meteorology and river flood development) but is not suitable for human activity monitoring at transportation system scales. With the exception of DND, temporal granularity is weakly represented in existing Canadian Government surveillance requirements.

Canadian Government surveillance requirements that reflect recently improved space-based SAR measurement capability and refined temporal granularity will probably be first defined by DND. These requirements will probably be driven by a need to observe cultural activities at fine spatial and temporal resolutions of several hours.

2.3 Surveillance requirements summary

- Canadian Government surveillance requirements are defined at the department level and respond to departmental mandates [2].
- There is no integrated set of Canadian government requirements for surveillance of the earth's surface [2].
- Requirements evolve with mandate.
- Requirements evolve with implementation technology.
- Formally approved requirements are often outdated due to technology advances.

There is a need for some department or agency to capture, update and maintain a statement of Canadian Government surveillance requirements.

- Is DND / DG Space the appropriate repository for Canadian space-based surveillance requirements?
- Requirements need to be forward-looking and need to have attached revision dates.
- Requirements need to be reviewed and updated on a regular cycle.

3 Space-based radar surveillance systems

Space-based radar surveillance capabilities exist at both a national and an international level. From a Canadian national viewpoint, the evolution of these capabilities both as Canadian owned and controlled resources and as internationally shared resources that have both Canadian and international components are of continuing interest.

3.1 Existing capability: December 2010

The properties of existing international radar surveillance satellites and systems form a baseline for the definition of future surveillance satellite constellation designs.

3.1.1 Canadian systems on orbit

Canada currently has two space-based radar systems on orbit. Both systems are designed as surveillance radars and are mainly applicable to the measurement and monitoring of natural phenomena.

1. RADARSAT-1 [14] is still operating (at 300% of its design life) and provides single channel SAR data suitable for environmental monitoring.
    a. Satellite mass: 2600 kg
    b. Radar parameters:
        i. Frequency: 5.3 GHz;
        ii. polarization: HH only;
        iii. Single beams: 5 m slant range resolution @ 45 km swath, 8.7 m slant-range resolution @ 100 km swath, 13 m slant range resolution @ 100 km swath;
        iv. Specialty beams: ScanSAR narrow, 50 m ground resolution @ 300 km swath: ScanSAR wide, 100 m ground resolution @ 500 km swath;
    c. Orbit parameters:
        i. Altitude: 795 km, inclination: 98.6º, ascending node: 18:00 local time, repeat cycle: 24 days;
    d. Operation parameters:
        i. Look direction: right of track;
        ii. Operating time per orbit 28 minutes;
    e. Lifetime:
        i. Launch: November 1995;
        ii. Design life: 5.5 years;
        iii. Current status: The system is still operating on back-up systems in November 2011. The on-board recorders have failed.
2. RADARSAT-2 [15] covers the environmental monitoring range of RADARSAT-1 with the addition of routine dual polarization, polarimetric, enhanced resolution and GMTI modes. RADARSAT-2 is used to partially fulfill some of the new cultural target surveillance requirements.
    a. Satellite mass: 2300 kg;
    b. Radar parameters:
        i. Frequency: 5.405 GHz, polarization per pulse HH, HV or VV,VH;

ii. Single beam, dual polarization: 3 m slant range resolution @ 30 km swath, 5 m slant range @ 45 km swath, 8.7 m slant-range resolution @ 100 km swath, 13 m slant range resolution @ 100 km swath;
iii. Single beam one polarization: 1.5 m slant range resolution @ 25 km swath;
iv. Specialty beams:
1. dual polarization: ScanSAR narrow, 50 m ground resolution @ 300 km swath: ScanSAR wide, 100 m ground resolution @ 500 km swath;
2. Pulse interleave polarimetry, 5 m slant range resolution @ 30 km swath,
3. GMTI single polarization: 3 m slant-range resolution @ 18 km swath; 5 m slant-range resolution @ 30 km swath; 8.7 m slant-range resolution @ 50 km swath; 13 m slant-range resolution @ 60 km swath;
4. Spotlight: 1.5 m x 3.5 m resolution @ 5 km x 10 km spot.

c. Orbit parameters:
i. Altitude: 795 km, inclination: 98.6º, ascending node: 18:00 local time, orbit repeat cycle: 24 days;

d. Operation parameters:
i. Look direction: right or left of the satellite track;
ii. Operating time per orbit: 28 minutes.

e. Lifetime:
i. Launch: December 2007;
ii. Design life: 7.5 years;
iii. Current status: The satellite is operating with full capability in November 2011.

Research based on the polarimetric and GMTI modes of RADARSAT-2 will likely yield modifications to the set of Canadian Government surveillance requirements.

Both RADARSAT-1 and RADARSAT-2 have high-inclination, retrograde (fixed time of day) orbits that lie on the dawn-dusk terminator. Except for the northern and southern orbit extremities, both satellites observe the earth's surface in the vicinity of 06:00 and 18:00 local solar time.

RADARSAT-1 is owned by the Canadian government and has a large commercial exploitation component to its tasking and use. RADARSAT-2 is commercially owned and operated. Canadian Government imaging requirements must be dealt within the context of commercial demand and there is a very tightly constrained set of priorities that can be used by government to override commercial use for national need.

3.1.2 International systems on orbit

International space-based imaging radar systems that are currently on orbit fall into three categories:

1. Individual satellites designed for earth resources monitoring and surveillance of large-scale cultural features;
2. Individual satellites and small constellations designed to provide both earth resources and cultural (urban) scale surveillance;

3. Individual satellites and small constellations designed to provide cultural scale (urban and finer scales) reconnaissance. The satellites in this latter group have primary military roles.

3.1.2.1 Individual satellites for earth resources monitoring

The ESA ENVISAT (ASAR radar) experimental satellite and the Japanese ALOS (PALSAR radar) experimental satellite fall into the first category.

1. ENVISAT ASAR [16]
    a. Satellite mass: 8200 kg;
    b. Radar parameters:
        i. Frequency: 5.331 GHz, polarization: HH, HV, VV, VH as a selected single channel or alternating polarization pair bursts;
        ii. Single beam: 10 m slant range resolution, single polarization @ 58 to 100 km ground swath;
        iii. Specialty beams: ScanSAR 150 m ground resolution @ 450 km swath;
    c. Orbit parameters:
        i. Altitude: 799.5 km, inclination: 98.55º, descending node: 10:00 local time, orbit repeat cycle: 35 days;
    d. Operation parameters:
        i. Look direction: right of track; Maximum operating time per orbit 30 minutes;
    e. Lifetime
        i. Launch: 1 March 2002
        ii. Design life: 5 years
        iii. Still operating in November 2011 and is expected to continue operation to 2013.
2. ALOS PALSAR [17]
    a. Satellite mass: 4001 kg;
    b. Radar parameters:
        i. Frequency: 1270 GHz, polarization: HH, HV, VV, VH as a selected single channel, 2 channel polarization pairs or pulse interleaved polarimetry;
        ii. Single beam: 5.35 m slant range resolution for single polarization operation @ 70 km ground swath; 10.7 m slant range resolution for dual polarized operation @ 70 km swath;
        iii. Specialty beams:
            1. Pulse-interleave polarimetry: 10.7 m slant range resolution @ 30 km swath;
            2. ScanSAR 71 m ground resolution @ 350 km swath;
    c. Orbit parameters:
        i. Altitude: 691.6 km, inclination: 98.16º, descending node: 13:00 local time, orbit repeat cycle: 46 days;
    d. Operation parameters:
        i. Look direction: right of track; Operating time per orbit 17.5 minutes;
    e. Lifetime:
        i. Launch: January 2006;
        ii. Design life: 5 years;
        iii. Failure report: April 22, 2011, Power system anomaly reported [18].

3.1.2.2 Individual satellites and constellations with fine resolution surveillance capability

The German TerraSAR-X and TanDEM-X satellites and the Italian Cosmo Skymed constellation fall into the second category.

1. TerraSAR-X / TanDEM-X constellation [27]
    a. Satellite mass: 1500 kg;
    b. Radar parameters:
        i. Frequency: 9.65 GHz, polarization: HH, HV, VV, VH as a selected single channel, 2 channel polarization pairs or pulse interleaved polarimetry;
        ii. Single beam:
            1. 1 m slant range resolution @ 15 km (dual polarization) and 30 km (single polarization) ground swath;
        iii. Specialty beams:
            1. Pulse-interleave polarimetry: 2 m slant range resolution @ 15 km swath;
            2. GMTI: 1 m slant range resolution @ 15 km swath;
            3. ScanSAR 16 m ground resolution @ 100 km swath;
            4. Spotlight: 1 x 1 m resolution @ 5 km x 10 km spot, single polarization;
            5. Spotlight 2 m x 2 m resolution @ 5 km x 10 km spot, dual polarization;
    c. Orbit parameters:
        iv. Altitude: 514 km, inclination: 97.44º, ascending node: 18:00 local time, orbit repeat cycle: 11 days;
    d. Operation parameters:
        i. Look direction right or left; Operating time per orbit: nominal 3 minutes, maximum 10 minutes.
    e. TerraSAR-X lifetime:
        i. Launch: 15 June 2007;
        ii. Design life: 5 years;
        iii. Current status: Operating at full capability in August 2011.
    f. TanDEM-X is almost identical to TerraSAR-X and is flown in close proximity (2 km to 800 m) to TerraSAR-X and operates interactively with TerraSAR-X.
        i. HRTI 3 DEM generation over 3 years (2011 to 2014);
        ii. two Satellite GMTI for can be used slow targets.
    h. TanDEM-X lifetime:
        i. TanDEM-X launch: 20 June 2010;
        ii. TanDEM-X design life: 5 years;
        iii. Current status: Operating at full capability in August 2011.
2. Cosmo Skymed constellation [19]
    a. Satellite mass: 1700 kg;
    b. Radar parameters:
        i. Frequency: 9.6 GHz, polarization: HH, HV, VV, VH as a selected single channel, 2 channel polarization pairs in a single channel "ping-pong" mode;
        ii. Single beam: 3 m ground resolution @ 30 km ground swath, single polarization, 5 m ground resolution @ 40 km ground swath, single polarization;
        iii. Specialty beams:

1. ScanSAR 30 m ground resolution @ 100 km swath: 100 m ground resolution @ 200 km ground swath;
2. Ping-pong alternating polarization: 15 m ground resolution @ 30 km ground swath;
3. Spotlight 1 x 1 m resolution @ 10 km x 10 km spot, single polarization.

c. Orbit parameters:
   i. Altitude: 619.6 km, inclination: 97.86º, ascending node: 06:00 local time, orbit repeat cycle: 16 days;

d. Operation parameters:
   i. Look direction: The primary direction is right of the flight track. There is a limited capability to look left of the flight track.
   ii. Operating time per orbit:
      1. strip-map and scan SAR: maximum 10 minutes per orbit with 75 minutes per day possible;
      2. spotlight: maximum 20 consecutive images per orbit;

e. Constellation: four satellites phased at 90º in the dawn-dusk orbit plane; minimum revisit time 12 hours;

f. Lifetime:
   i. Launch dares: 8 June 2007, 9 December 2007, 25 October 2008, and 5 November 2010;
   ii. Design life: 5 years per satellite;
   iii. Constellation operational lifetime: 15 years;
   iv. Current status: All satellites operating at full capability in November 2011.

3.1.2.3 Reconnaissance satellites and constellations

The German SAR Lupe constellation, Israel's TecSAR satellite and India's Risat-2 satellite fall into the third category. China's Yaogan 1, 3, and 10 satellites may be members of this group and the closely-held technical specifications of this group suggests that they are primarily designed for military use.

1. SAR Lupe [20]
   a. Mass: 720 kg;
   b. Frequency: X-band 9.65 GHz, single polarization HH;
   c. Single beam: 1 m ground resolution @ 8 km x 60 km swath;
   d. Specialty beam: 0.5 m spotlight@ 5.5 km x 5.5 km;
   e. Orbit altitude 480.1 km to 503.4 km elliptical, inclination 98.2º;
   f. Operation: mechanical pointing, 25 images per day;
   g. The constellation operates 5 satellites in three orbital planes with orbital planes 1 and 2 separated by 64º and orbital planes 2 and 3 are separated by 65.6º.
   h. Data delivery: direct down-link and inter-satellite links;
   i. Lifetime:
      i. Launch dates: 19 December 2009, 2 July 2007, 1 November 2007, 27 March 2008, and 22 July 2008;
      ii. Design life: 10 years per satellite;
      iii. Current status: All satellites are operating at full capability in November 2011.

TecSAR [21]
   a. Mass: 395 kg;

b. Frequency: X-band 9.59 GHz, single polarization VV;
c. Single beam: 8 m and 3 m resolution strip-map;
d. Specialty beams:
    i. < 1 m resolution spotlight (10 cm reported Jerusalem Post 21, January 2008);
    ii. < 1 m resolution spot mosaic;
e. Orbit altitude 450 km to 580 km, orbit inclination 41º;
f. Lifetime:
    iv. Launch: 21 January 2008;

2. Risat-2 [22]
    a. This is a TecSAR instrument at 450.6 km to 549.7 km altitude and 41º orbit inclination. Its role is military reconnaissance.
        i. Launch: 20 April 2009.
3. KOMPSAT-5 (Korean Multi-purpose Satellite 5) [23]
    a. This development, which started in the middle of 2005, will be launched in 2011 and its payload will be an X-band SAR operating in a Dawn-Dusk orbit between an altitude of 500 km to 600 km. The primary mission of the KOMPSAT-5 system is to provide high resolution mode SAR images of 1 meter resolution, standard mode SAR images of 3 meter resolution and wide swath mode SAR images of 20 meter resolution with viewing conditions of the incidence angle of 45º using the COSI (COrea SAR Instrument) payload.
    b. Frequency: 9.66 GHz (X-band);
    c. Active phased array;
    d. 550 km sun-synchronous orbit, 14.5 orbits/day.
4. Yaogan [24]
    a. SAR satellites, No radar information has been found.
    b. Yaogan 1: 628 km to 629 km altitude, orbit inclination 97.8º;
        i. Launch: 27 April 2006;
        ii. Failed 4 February 2010.
    c. Yaogan 3: 635 km to 637 km altitude, orbit inclination 97.8º
        i. Launch: 12 November 2006;
        ii. Yaogan 10: 633.9 km to 636.4 km , orbit inclination 97.8º;
        iii. Mass: 2700 kg;
        iv. Launch: 22 September 2010.

3.2 Near future international capability

1. Sentinel 1 [24]
    Earth resources observation and ship surveillance are the design drivers. A public service data acquisition/distribution policy will be used where users are not charged for the data provided to ESA participants.
    a. Satellite mass: 2280 kg;
    b. Radar parameters:
        i. Frequency: 5.405 GHz, polarization: single channel, HH, HV, VV, or VH; channel pairs HH, HV or VV, VH; Wave Mode HH or VV;
        ii. Single beam:
            1. 5 m ground range resolution @ 80 km ground swath; 5 m x 20 m resolution @ 250 km swath interferometric mode;
        iii. Specialty beams:
            1. ScanSAR 20 m ground resolution @ 400 km swath;

        2. Wave mode 20 km x 20 km vignettes @ 100 km intervals;
   c. Orbit parameters:
      i. Altitude: 693 km, inclination: 98.18º, ascending node: 18:00 local time, orbit repeat cycle: 12 days;
   d. Operation parameters:
      i. Look direction: right of the flight track;
      ii. Operating time per orbit:25 minutes for strip-map and 74 minutes for wave mode;
   e. Constellation: two satellites in the same orbit plane with unpublished orbit phasing;
   f. Lifetime:
      iv. Planned launch: Sentinel 1a, end 2011, Sentinel 1b, 2014;
      v. Design life: 7 years.
2. SAOCOM [26]
   a. The SAOCOM (Satellites for Observation and Communications) series is Argentina's first Remote Sensing mission carrying an L-band full polarimetric SAR. Preliminary Design Review 13 September, 2011;
   b. Date of launch: scheduled for 2012;
      Orbit Height: 686 km;
      Orbit Type: Sun-synchronous;
      Revisit time: maximum 16 days.
3. Cosmo Second Generation (CSG)
   a. Planning in progress (approved program);
   b. Planned launch date: October 2015 [28];
   c. Design life: 7 years;
   d. Orbit inclination 97.8º;
   e. Orbit plane: dawn-dusk.
4. TerraSAR-X2 [27]
   a. Planning is in progress. The phase A studies are scheduled to be completed in October 2011. The intent is to evolve this system for long-term operation.
   b. Planned Launch date: 2016;
   c. Features:
      i. Fine resolution, 600 MHz bandwidth/channel;
      ii. Multi-channel SAR;
      iii. Limited digital beam forming;
      iv. On-board Automatic Identification System (AIS);
      v. 800 Mbps downlink;
      vi. 3 satellite constellation option.
5. Information Gathering Satellites (IGS) [29]

   This is a series of Japanese high resolution optical and radar satellites designed primarily for military use. The B series of satellites carries a SAR payload. IGS B was launched in March 2003, and IGS 4B was launched in February 2007. Both of these satellites have failed. The government's plan was to build a network of four intelligence satellites; two with radar devices (B series), and two optical satellites (A series) that capture images in daytime and through clear sky. Japan is now planning to replace the two radar satellites. Launches are planned in 2011 and 2012.

3.3 Future Canadian space system development

Recent experience has shown that Canadian national surveillance requirements favor a nationally owned and operated surveillance capability [30] to complement available commercial sources and to provide international horses to trade. Under international trade agreements, there is no guarantee that Canadian commercial components will be long-term Canadian assets and there is no guarantee that Canadian companies that reside in Canada will remain under Canadian control. Companies are commercial commodities.

The evolution of Canadian space systems will occur in the context of an increasingly complex international environment that has both commercial and national components.

Recent technological advances have focused space-based radar developments in the direction of constellations of small satellites that have constrained individual capabilities and can be compensated or augmented by the joint properties of all constellation members. Canadians (through their space systems development agent, CSA) have accepted the surveillance constellation model (RCM) and now need to focus on reducing the cost and increasing the capabilities of individual constellation members and on creating the infra structure needed to operate, maintain and evolve Canadian national components.

Learning from a number of commercially available international systems will provide insights that will drive the development of new Canadian surveillance requirements. This is particularly true in the areas of cultural activity surveillance and transportation system surveillance. Initial drivers for new surveillance requirements will probably come from sovereignty and security concerns but evidence is growing to support requirements for transportation infra-structure surveillance. These will be sensitive to time-of-day variation and are not well supported by the available complement of space-based radar systems.

Although a number of low-cost international reconnaissance radars have been deployed, there are no Canadian radar reconnaissance satellites currently planned in the near term. Canadian reconnaissance requirements are identified in the draft DND surveillance requirement set in Annex A.

3.3.1 Combining complementary Canadian and international assets

A significant component of Canadian space system development strategy will be international negotiations to combine resources from various owners to support Canadian surveillance needs in the context of the shutter control policies of the negotiating parties.

At the present time there is a *de facto* international constellation of radar satellites that can be employed to make radar observations of the earth's surface in the vicinity of 06:00 and 18:00 (local solar time) over much of the earth's surface. Although there has been some experimental work on how data from different sensor systems can be used in a complimentary fashion, there have been no systematic examinations of how data from members of the constellation of active national and international radars can be employed to address Canadian surveillance requirements.

At the present time, Canadian radar reconnaissance needs must be satisfied by negotiated agreements with international sources.

3.3.2 Canadian development directions

3.3.2.1 International agreements

Present and future Canadian space-based radar systems exist and will exist in the context of internationally owned and operated space-based radar surveillance and reconnaissance systems. The international systems are owned and operated by a mixture of private and public interests. Provided that Canada develops and maintains publicly owned space-based systems and the associated ground infrastructure that can provide data services desired by international partners, there are trading possibilities that can be used to augment some Canadian surveillance and reconnaissance capabilities to support requirements. International discussions headed by DND and CSA are in progress.

The development of Canadian radar satellite systems needs to include international trade agreements as a design component. These will necessarily be linked to Canadian data policy evolution.

3.3.2.2 Canadian constellations of space-based radar systems and complementary sensors

Canada is proceeding with the development of a surveillance radar constellation as a national resource. For marine applications, the fusion of radar detections of ship targets and broadcast AIS data from marine traffic provides an expanded target-information set and allows cross validation of the two information sources. There are two space-based approaches to acquiring the two data streams needed for fusion:

1. Combine the radar sensor and the AIS receiver on the same platform so that the two data sets are spatially and temporally coordinated. This is the approach proposed for RCM and has the advantage that data fusion is simplified.
2. Fly separate surveillance radar and AIS monitoring satellites and correlate the radar data with generated AIS tracks. This approach is modelled by the M3MSat project. For this approach to work successfully, a large constellation of low-cost AIS monitoring satellites is required and the AIS satellite orbits must be coordinated with the surveillance radar orbits.

Both approaches to combining complementary radar surveillance outputs with AIS reports require coordinated ground processing facilities.

Other space-based sensor types that can routinely complement surveillance radar constellation measurements have not been considered for constellation implementation at this time.

3.4 Space-based radar surveillance systems summary

- There are and will be opportunities to negotiate the existence of an international surveillance and reconnaissance space radar constellation. Success in negotiations will be contingent on Canadian "horses to trade".
    - There are currently four Canadian and international single satellite and two small-constellation surveillance radar systems on orbit that can be engaged to provide elements of a collaborative, international, *de facto,* surveillance constellation.

    - There is one international reconnaissance radar constellation on-orbit that could be integrated into a *de facto*, collaborative, international, surveillance and reconnaissance constellation.
    - A two satellite surveillance radar constellation will soon be launched by ESA.
    - A three satellite surveillance radar constellation, RCM, is under development by Canada.
- Canadian development of an expanded, indigenous, surveillance radar constellation (RCM with RNG augmentation) is in progress.

4 Developing Canadian space-based radar surveillance constellations

The process of developing and operating a space-based surveillance radar constellation requires the creation of coordinated programs that:

1. Update and refine surveillance requirements and develop and execute long-term plans;
2. Create and manage the space-based resources;
3. Create and manage the ground-based resources;
4. Create and manage an infra-structure that extracts, correlates, stores and distributes information obtained from surveillance systems to make this information available to user communities in a timely manner.

These four programs are the legs needed to support an effective surveillance constellation.

From the DND viewpoint the development of a fully functional Canadian surveillance constellation follows from high-level guidance for desired outcomes that can be summarized as:

DND/CF has the ability to conceive, design and deliver space systems to meet Canada's defence needs [33].

4.1 Space-based component

4.1.1 Constellation properties

Space based sensor constellations differ from individual surveillance satellites in several important ways:

1. The lifetime of a constellation is much greater that the lifetime of any member spacecraft.
2. The surveillance roles of a constellation can evolve over its lifetime by replacing worn out components with upgraded satellites and by augmenting constellation member capabilities with the addition of new components (satellites).
3. Individual constellation spacecraft and sensor systems are generally more specialized than those used in single satellite systems and have a more limited capability.
    a. Constellation members that have been designed to only fill formally stated requirements will become dated before the end to their useful lives.
    b. Constellations will need to contain a few "advanced" members that test augmentations to meet evolving needs.
    c. Constellations can and should contain a mixture of sensor types to meet some surveillance requirements.
    d. Responsive de-orbiting mechanisms are required to safely remove end-of-life constellation members to reuse their orbital slots.
    e. Continuously supported airborne research facilities that explore sensor design evolution are critical parts of a cost-effective space-based constellation system.
4. The command and control infrastructure required for surveillance constellations is significantly more complex than that used for individual satellites.
5. Because of the very large data volumes expected from surveillance constellations, highly automated ground-based and on-orbit information extractions systems will be required.

From a surveillance viewpoint there are two fundamentally different classes of space system constellations.

1. A satellite "herd" constellation is designed to cover an observation region with a cluster of measurements near the same local time of day. Constellations of this type allow one or two observations of any selected geographic area each day at local times separated by multiples of twelve hours. Surface events or activities that vary with time of day cannot be observed. The Canadian Radar Constellation Mission, TanDEM-X and COSMO Skymed are all members of this constellation type.
2. A "dispersed-orbit-plane" constellation provides a smaller daily coverage area at any selected terrain point in exchange for increased temporal resolution and shorter revisit gaps. The SAR Lupe constellation is the sole member of this type.

Although a satellite herd meets sea-ice monitoring and coastal ship detection requirements, it has limited use for monitoring transportation dynamics and other dynamic phenomena. Radar observations used to support meteorological models should be available at approximately six hour intervals.

The selection and implementation of the correct mix of satellite herd and dispersed orbit plane resources is a critical outcome of the long-term planning effort.

4.1.2 Canadian requirements development

The Canadian surveillance requirements that have been defined to date are best suited to monitoring surface events that can be adequately described by data samples taken at twelve hour and longer intervals. Canadian Government requirements are largely silent on urban surveillance and on transportation monitoring. DND has developed a draft set of Canadian surveillance and reconnaissance requirements to meet operational needs (Annex A).

At the high level, DND requirements are evolving from the recently issued Strategic Capability Roadmap [31], the C4ISR Capability Development Plan [32] and the draft National Defence Space Strategy [33]. These documents capture current thinking on surveillance development directions needed to support Canadian Forces mandates now and in the near future and provide top-level direction for the DND component of Canadian Surveillance requirements definition. They are expected to evolve over time and will support the on-going DND requirements definition process. The draft DND surveillance requirements outlined in Annex A provides a snapshot of the present stage of the requirements definition process.

To effectively use surveillance requirements to define the evolution of space systems, a pro-active process that focuses on probable requirements at the mid-life points of new system components needs to be developed. Given the present time lags between mission definition and fielding equipment, missions need to be driven by anticipated needs up to ten years in the future.

A requirements evolution process that is driven by C4ISR Capability needs[1] and is based on evolving research results, international technology trends and public policy trends is a critical part of the continuing development, maintenance and operation of the Canadian space-based surveillance system components.

[1] DND has created a surveillance capability development strategy and plan [2,3]. Similar documents are required from other Canadian government departments to provide the full Government of Canada picture.

4.1.3 Canadian space-based radar surveillance system plan elements

At present the space component of the Canadian space-based radar surveillance system consists of the aging RADARSAT-1 spacecraft and the recent RADARSAT-2 spacecraft. RADARSAT-1 is very near its end of life and demand for its services has been rapidly declining in favor of the more capable RADARSAT-2. RADARSAT-1 has become technologically irrelevant at the correct point in its life cycle. RADARSAT-2 is a commercially owned and operated spacecraft.

RADARSAT-2 will be augmented and eventually replaced by a radar satellite constellation whose first elements, the RCM, will consist of three SAR spacecraft to be launched between 2016 and 2017. RCM will be a government owned and operated satellite herd constellation that has been designed to provide contiguous large-area coverage to support the following primary missions:

1. Ice and iceberg monitoring for:
    a. The Canadian east coast;
    b. The Canadian Arctic;
    c. The Great Lakes;
2. Marine wind measurements on both coasts and the Great Lakes;
3. Oil pollution monitoring in the east and west coast shipping routes and on the Great Lakes;
4. Ship detection over North American outer zone (to 1200 nm from the coast).

Although the ship detection problem has been a primary design driver, a number of secondary missions use narrower swath, higher resolution modes of the satellites. The satellite orbit structure for the constellation will reduce the repeat-pass time separations used for coherent change detection and interferometric SAR elevation mapping to nominally 4 days.

The individual RCM satellites will be less capable than RADARSAT-2 and many of the current international SAR satellites for high resolution and vehicle motion measurements. The RCM constellation does provide spotlight mode and enhanced coherent repeat intervals that will be useful for monitoring urban and cultural feature changes. It will not address the time-of-day sensitivity issues that are significant for some evolving DND needs and for dynamic response to some classes of natural disaster.

Technologically, the RCM satellites use transitional designs closely related to the RADARSAT-2 architecture.

Programs to address the shortcomings of the RCM design and to extend the Canadian Surveillance capability are in progress.

1. Several approaches to the use of space-based AIS (Automatic Identification System) measurements for marine surveillance support are being examined:
    a. the Orbcom AIS receiver system;
    b. ComDev and Norwegian nano-satellite investigations;
    c. DRDC M3MSAT experimental satellite;
    d. RCM AIS receivers.
2. A new space-based radar design paradigm (WiSAR) is being investigated to reduce the unit cost and weight of new radar constellation members and to improve capability. Systems of this class represent possible augmentations to RCM either as herd members or as dispersed-orbit-plane components.

3. DND is examining its surveillance requirements in the context of the imminent Space Strategy document to identify and formulate expanded requirements that express present and near-future surveillance needs. A draft requirement set has been generated.
4. DND and CSA are collaborating on the definition of next-generation spacecraft that will expand and augment the RCM constellation. The draft DND surveillance requirements set is being used to define the missions for and characteristics of the next-generation sensors.

4.1.4 Space segment development

In the context of a long-lived radar surveillance constellation, the number, forms and functions of the orbital components will evolve in response to the evolution of available technologies and the content and shifting importance of surveillance requirements. Since the key drivers are dynamic, the constellation contents need to be dynamic. This implies that the traditional, project-based approach to satellite development needs to be replaced with a program-based spiral development strategy that progressively executes an evolving long-term plan. This change in approach requires the development of a surveillance capability sustainment policy.

4.1.4.1 Functional evolution and augmentation

SeaSat-A, launched in June 1978, established space-based synthetic aperture radar as a feasible and significant remote sensing tool. Evolution of spacecraft, orbit control and ground processing technologies through ERS-1 (1991), JERS-2 (1992), ERS-2 and RADARSAT-1 (1995), ENVISAT (2002), ALOS (2006), TerraSAR-X and RADARSAT-2 (2008) resulted in the creation of radar remote sensing and surveillance technologies that have both national and corporate value in the international community. Each new spacecraft introduced advances in space-surveillance technology.

Space based radar surveillance evolved from single satellite capability to constellation-based capability with five SAR Lupe satellites launched from 2006 to 2008, four Cosmo-Skymed satellites, launched from 2007 to 2010, and the two satellite TerraSAR-X, TanDEM-X constellation launched in 2007 and 2010. Individual satellites in a constellation context are more specialized than the larger, individual satellites but have lower unit cost and the functions that can be performed by the constellation can be enhanced by expanding the constellation with complementary instruments and by replacing failing constellation members with improved technology and / or new functionality.

Canada is entering the space-based radar constellation surveillance era with the launch of a three satellite constellation, RCM, starting in 2016. The initial three satellites will not meet the surveillance coverage area or observation frequency specifications from either defined [4] or developing (Annex A) DND surveillance requirements but will meet enough OGD (Other Government Department) requirements to be valuable. Additional satellites that are not replicas of the initial three constellation members will be required for constellation augmentation to meet the highest priority DND requirements. CSA-sponsored definition studies for RADARSAT Next Generation satellites are in progress in November 2011. The number of additional constellation satellites and their functional specifications will be determined by priorities defined in the long-term constellation plan. As the constellation augmentation is completed, it will be time to replace the initial three spacecraft with evolved designs that apply the available technology of the day to the evolving surveillance requirements. History suggests that significant advances in space system technology appear every three to five years.

The controlled evolution of the Canadian surveillance constellation will be closely linked to space-based radar technology and exploitation R&D.

4.1.4.2 Constellation maintenance and satellite replacement

Under the defining assumption of this document, the lifetime of a constellation of space-based sensors greatly exceeds the lifetime of any satellite in the constellation. Constellation performance not only depends on the capabilities and performance of any given member, but also depends of the physical position of individual satellites in the constellation formation. As satellites fail, they must be removed and replaced in a timely manner.

1. Constellation designs need to include at least one position for a replacement satellite.
2. Each satellite in the constellation must be equipped with a repositioning capability that can remove it from its current orbit position in a reasonable (hours to weeks) time.
    a. Each satellite must be equipped with a de-orbiting capability that can safely remove it from orbit fast enough that it does not become a hazard for lower altitude orbiting systems.
        i. The optimum de-orbit time is still not determined but when the orbital debris context is included in deliberations the time from a satellite's removal from its operating orbit to its re-entry into the earth's atmosphere could easily be less than a year.
        ii. The time horizon for the implementation of de-orbiting solutions is believed to be less than a decade.
    b. In the event that the faulty satellite's ability to receive and act on de-orbit command fails, deployable de-orbit systems (robotic space tugs) must be positioned to intercept the failed vehicle, attach to it and perform the required removal functions.
3. Robotic, on-orbit servicing is likely to become viable over the lifetime of a constellation.

For some constellation operating scenarios, it is essential that all required constellation members perform their functions reliably at the required times.

1. It is advisable to include self-diagnosis and self-repair functions in the satellite control system and sensor designs.
2. A constellation member that is positioned as a "hot" spare may be required for some critical surveillance requirements.
3. TT&C links need to be positioned to correct detected faults without blocking high priority activities or required space-to-ground data delivery links.

Another key element of constellation maintenance is satellite replacement. This implies that the space segment development and construction process proceeds at a pace that allows satellites to be replaced when they fail and that replacement satellites can be launched when required. The replacement satellite availability, when coupled with constellation performance evolution, is best handled by a program that is continually developing the next unit and has a regular launch cycle. Timely launch requires that a guaranteed access to launch is obtained either through negotiation with launch providers or by some other means. Launch availability and cost reductions could be negotiable if long-term plans include regular launches scheduled over a period of several years.

4.2 Ground-based component

The ground infrastructure needed to operate any space system has three major parts:

1. Space system control,
2. Data reception and archive, and
3. Data exploitation and information distribution.

The details of the infrastructure needed for a surveillance constellation differ from those required for a single surveillance satellite by more than just scale.

4.2.1 Constellation control and TT&C

In the current model used to support space-based surveillance activities, sensor tasking is generated by an order desk and results in acquisition commands being sent to a satellite. The acquisition commands define the satellite operating mode, the acquisition times and the downlink receiving station. An order de-confliction process is used by the order desk to assign data acquisition sequences for each observation area.

Current satellite control facilities and processes are based on the operation of single satellites. New processes need to be developed to support the operational use of space sensor constellations. In particular:

1. Constellations allow three different operating scenarios:
    a. All constellation members operate as a single system and have closely coupled operating parameters. In the longer term self-organized control of constellation members could be advantageous for continuous, routine operation to observe fixed areas.
    b. Subsets of the constellation members operate as a single system and other members are independently assigned.
    c. All constellation members are assigned different tasks and are programmed independently.

   The number of possible operating combinations increases the complexity of the satellite acquisition assignment process over that required for a single satellite.
2. For satellite herd constellations the time separation of constellation members imposes response time stresses on TT&C facilities. Where the satellites are in close physical proximity (e.g. TanDEM-X) different TT&C channels need to be assigned to each satellite. In some cases two satellite communications antennas may be required at each TT&C station.
3. Diagnostics and maintenance activities that apply to any satellite in a constellation can impact the performance of the entire constellation for some operating scenarios.
    a. TT&C stations should be placed in locations where scenario 1.a. operation is unlikely.
    b. Since satellite programming, testing and calibration activities can interfere with (block) data acquisition, TT&C stations should be located in regions that have a low probability of intense acquisition activity.
    c. At least two TT&C stations in geographically separated locations are required. A larger number of stations is advantageous.
4. TT&C stations should be remotely operated from a mission control facility to minimize operating cost.
5. Enhanced encryption of TT&C links will be required to safeguard national interests. For deployed stations or stations in foreign territory, there are encryption-key secure-transportation issues that must be dealt with.
6. Space-to-space relay links should be considered for satellite programming activities.

    a. This approach is particularly valuable for responsive, deployed receiving stations that are needed to meet Canada's international obligations.
    b. This approach can reduce the number of inter-connected ground-based TT&C facilities required to minimize service interruptions.
    c. This approach presents additional countermeasure opportunities to national opponents.
7. Calibration of space-based radar sensors is a well developed art for current single satellite systems. For a constellation of radar sensors, the calibration of each constellation member must be established and maintained. Current approaches to sensor calibration will need to be revised, and the calibration workload will need to be increased to support calibration maintenance for a constellation.

4.2.2 Data capture and receiving station design

Current satellite control facilities and processes are based on the operation of single satellites. The architecture and function of satellite constellations will have impacts on receiving station design.

1. For satellite herd constellations the temporal spacing of data downlinks can impose time stresses on antenna control systems and on data handling responses.
    a. Some constellation designs and use scenarios will require at least two active data reception antennas and separate data channel assignments for sequential satellites.
2. Several active receiving stations should be built and sited to minimize data latency for time-critical applications.
    a. DND is building receiving stations on the east and west coasts under the Polar Epsilon project to support its marine surveillance mandate. The stations are designed to consist of un-manned reception stations that are remotely controlled from control/data handling/processing facilities which, in turn receive tasking from and deliver information to DND Maritime Security Operations Centers. These stations are expected to start operation in fall or early winter 2011. Incorporation of data reception for other Government of Canada operations was not included in the initial receiving station design but will become a use factor.
    b. DND is reviewing the construction of a northern ground station under the Polar Epsilon project. Project definition for this capability is in progress. Inclusion of broad Government of Canada service will depend on agreements reached and direction received by the project office. No date has been defined yet for the start of station operation.
3. For routine surveillance with known parameters and long-term requirements, on-board processing capabilities, incorporated into constellation satellites, is a possible development direction.
4. The creation of deployable ground stations to support deployed Canadian personnel should be included in development plans.

4.2.3 Data exploitation and information distribution

Surveillance requirements flow from surveillance strategies and plans and define surveillance tasks to accomplish. The requirements outline what information is required and when it is needed. The surveillance tasks are directly linked to processes that identify information requests and define information delivery needs.

The current data exploitation and information delivery model has the following form:

1. The agency responsible for a surveillance activity defines the data required to provide the necessary surveillance information and identifies the data provider.
2. For space-based data, data specifications and acquisition times are used to generate data orders for the satellite operator.
3. The operator selects viable acquisitions and programs the satellite to acquire data.
4. Data are down-linked to a designated receiving station, are archived and are converted to data products for delivery to the ordering agency.
5. The agency responsible for the supported surveillance task extracts required information from the data products and combines the information outputs with information from other sources to generate surveillance products.
6. The surveillance products are used to define required actions.

Depending on the capabilities resident in the surveillance agency, information extraction will be performed by resident agency personnel, by contractors or by some combination of both. Discussions in [2] indicate the scope of the information extraction and distribution problem for GoC users.

Due to anticipated increases in data outputs from a constellation of space based sensors, this model may need to be modified or replaced.

Public release of the data used for information extraction and the ability to share these data with international partners is governed by current Canadian data policy [3].

4.3 Canadian space-based radar surveillance constellations summary

- Surveillance radar constellations can be based on herds of radar satellites, satellites in dispersed orbit planes, or combinations of both.
- The lifetime of a surveillance constellation can greatly exceed the lifetime of any member satellite.
- The development and use of Canadian surveillance radar constellations should be based on GoC surveillance requirements.
    - Requirements need to flow from surveillance capability needs.
    - This is a work in progress.
- Augmentation of a constellation by adding satellites and replacement of satellites in a constellation needs to capture and foster technology innovations to add capability and reduce cost.
- Constellation maintenance requires both the replacement and de-orbiting of failing satellites.
    - Effective de-orbiting technologies need to free up a constellation orbit slot in a short time and need to remove the failed satellite from orbit in an expeditious manner.
        - Suitable de-orbiting technologies are a work in progress.
        - There will soon be an international requirement for satellite designs to include de-orbiting provisions.
- The development of viable surveillance constellations implies a re-design and augmentation of the ground systems that task the satellites, command the satellites, calibrate the satellite sensors, maintain the satellites and sensors, receive data from the satellites and develop user products from received data.

- TT&C and receiving station tracking for constellations are more stringent that for single satellites.
  - Mitigation approaches need to be defined and addressed.
- Constellations significantly increase satellite maintenance and calibration workloads.
  - The problem needs to be quantified and the issues addressed.
  - Significant changes to satellite tasking an operating procedures and resources will be required.
- When the constellation becomes the surveillance tool (instead of seeing individual satellites as surveillance tools) a re-design of the tasking and operation systems will be required.

- The anticipated large increases in output data from constellations (as compared to single satellites) will force re-designs in the data processing, information extraction and information dissemination systems.

5 Procurement process strategy

One of the most costly risks associated with long lived systems, such as space-based sensor constellations and their associated infrastructure, is the risk of components becoming irrelevant because of poor forward thinking, decision delays and long procurement processes.

5.1 Contracting delay mitigation

A key delay mitigation strategy is to change the procurement definition approach.

1. The current, piecemeal, space-system development model addresses each component as an individually developed and funded project. Each component must be approved and acquired through a lengthy bureaucratic process which is repeated for each acquisition.
2. A better approach is to create one or more development program(s) that has (have) a defined funding line(s) and is (are) based on a set(s) of capability needs to be met over a long period of time (for example, 20 years). A program of this type would be defined in terms of Canadian Government surveillance policy and on departmental C4ISR Capability plans. Program definition would absorb most of the approval steps so that these do not need to be repeated for program components.
    a. Each program's guiding principles would be reviewed and refined at regular intervals.
    b. Individual space-based or surface elements would be developed as "child" processes for which the major justifications would be captured in the program definition and in the evolving program plan.
    c. Governance would be executed at the program level.

    When a program is thought of as a capability delivery mechanism, the definition and approval process represents the baseline cost of the capability. This cost exists whether or not the program is ever delivered. It consists of measureable hard costs (personnel time) and estimated soft costs (opportunity loss, influence loss, etc.). Best practice is to include as many current recurring costs as possible into the program definition (as non-recurring costs) and to minimize the remaining recurring costs for the supply of items and resources needed to execute the program. The baseline cost and the cost of recurring elements need to be captured explicitly in the life-cycle cost of the capability.

5.2 Contract award, phases and risks

Once a build project is approved, current procurement and contract management practice is very cumbersome and needs to be re-thought:

1. Is there a more efficient contractor selection and contract approval process that can be developed and used?
2. Is there a more effective way to manage contract execution phases to achieve best performance without massive bureaucratic overhead?
    a. Should the development phase steps be more closely tailored to the work to be done? One size does not fit all.
    b. Risk assessments need to capture costs and delays from all sources as risks.
        i. Civil service time resources have costs and these costs need to be captured as risk elements.
        ii. Decision time has a cost and time-lag costs need to be captured as risk elements.

iii. Process is a tool not an objective. Process costs (time and personnel) are risks that need to be traded against performance risks and accountability risks.

d. Risks need to be managed, not avoided. The engineering cost-bathtub model shown in the cartoon in Figure 1 provides a good tool to manage risk trade-offs provided that all costs are included in the analysis.

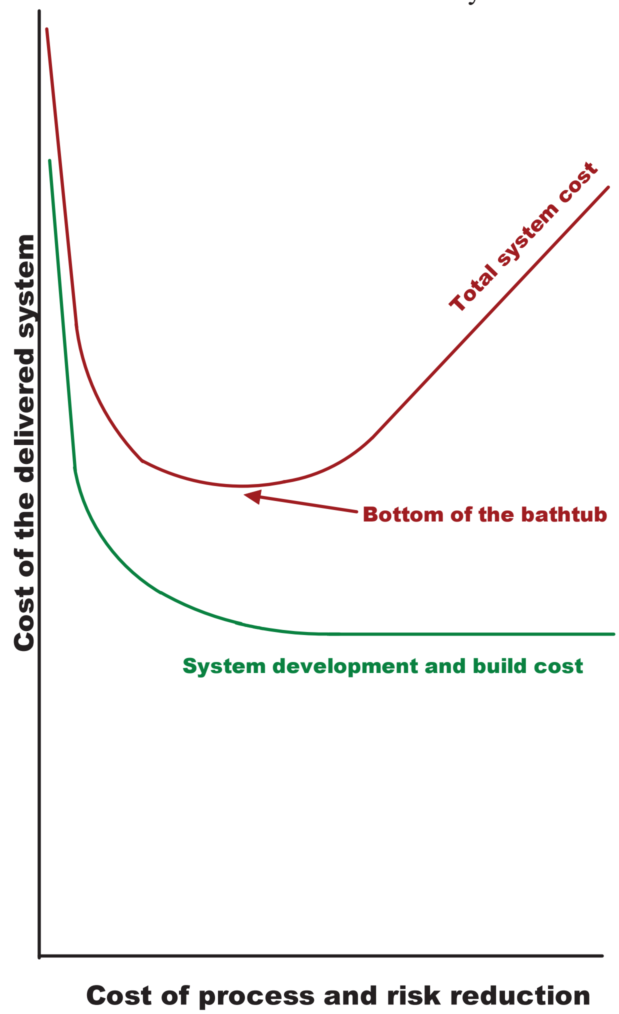

Figure 1: Cartoon of the engineering bathtub cost model.

The challenge for any development is to design process and risk reduction costs to reach the bottom of the bathtub at the lowest total cost.

5.3 Procurement process strategy summary

- The existing government procurement process is poorly suited to the development of a surveillance satellite program.
  - It is based on batch-mode thinking.
  - Procurement time delays are excessive.
  - Procurement does not mitigate program risks; it has become a significant program risk.

- A program-based approval and procurement strategy needs to be developed.
    - Delay should become a captured cost element.
    - Civil service work load should become a captured cost element.
    - Program approvals should shift responsibility and accountability towards the working level so that approval elements that require protracted processes are attached to the program and not to work within the program.
    - The program should have an operating budget that is commensurate with its mandate and responsibilities.
    - Senior oversight should apply to the program level.
- Contracting processes and oversight may need to be re-thought.

6 Straw-man roadmap

For planning purposes it is assumed that space based radar and supporting space-based sensor systems will be deployed as a constellation of satellites that contains both satellite herd and dispersed-orbit-plane components. This constellation will have a design life of at least twenty years. It is further assumed that:

1. A critical mass of the space-based Canadian radar surveillance capability will be owned and controlled by the government of Canada as the Canadian national surveillance system.
2. Constellation members will have a design lifetime between five and seven years.
3. Canadian surveillance requirements will the reviewed on a three year cycle and incorporated into the surveillance capability delivery plan.
4. The steady-state surveillance constellation will contain at least six satellites (this is a nominal limit and not a hard limit).
5. New sensor, spacecraft and mission designs will be actively pursued and supported.
    a. A four year program review cycle is proposed.
6. The surveillance constellation may be augmented by a reconnaissance constellation.
7. Negotiated data and/or control access trades with space-faring international partners will be used to augment the capabilities of the Canadian national space system.
8. Negotiated data trades with (or purchases from) commercial entities will be used to augment functions performed by the Canadian national system.

6.1 Surveillance radar constellation model

Following from discussions in section 4, a notional roadmap for Canadian surveillance radar constellation development, maintenance and operation rests on three closely linked, long-term programs, illustrated in Figure 2, that employ a spiral development model for functional evolution and capability sustainment. These are:

1. A requirements development program provides guidance for surveillance constellation development and operation.
    a. Requirements development is a Canadian government activity that:
        i. Collects surveillance needs from Canadian government departments;
            1. The collection process could be based on a surveillance workshop that is held every two years.
        ii. Evaluates and collates expressed surveillance needs;
            1. The evaluation and collation process could be a multi-department working group that combines policy and technical experts to combine related needs into logically related groups, identifies sub-groups that have common factors and determines quantitative parameters that best describe the grouped surveillance needs.
        iii. Defines the relative importance (ranking) of the accepted surveillance needs.
            1. The ranking process could be done by the same working group or by an interdepartmental committee that defines the relative importance of the filtered surveillance needs on government-wide and department scales and sets desired time lines for

execution. This group would also be responsible for obtaining high level approval in a timely manner.

iv. Reports the Canadian surveillance requirements on a fixed cycle (nominally 4 years).

1. The Canadian government surveillance report describes the current Canadian surveillance requirements that are under consideration at the reporting date and indicates those that have received high level approvals from various departments. The report could include departmental sub-sections that identify specific needs that have a departmental focus.

v. For DND (and possibly the Government of Canada) leadership for requirements development should be provided by DG Space (or his superior).

2. A satellite development program that contains and / or manages all resources needed to develop surveillance satellites is defined, approved and activated.

a. Satellite development is a Canadian government-supported activity that uses both internal and industrial resources to:

i. bring new technologies to a suitably high readiness level for satellite construction;

1. A steady input of technology and implementation ideas from the research community is expected.

ii. conduct surveillance satellite definition activities; and

iii. build, test, and launch satellites.

b. Satellite development will have a continuing funding line that is augmented by focused Treasury Board funding.

i. One of the functions executed by the satellite development program will be funding acquisition.

c. Satellite development is designed as a continuous-flow program process (as opposed to a burst-mode project process).

i. Satellites will be ready for launch at nearly uniform intervals (for example: one per year for a six satellite constellation whose members have a six year design life).

ii. Activities related to successive satellites will proceed in parallel (thus eliminating many start-up and close-out costs).

iii. Development will be based on the active management of total risk (including the risk of obsolescence) and not on risk aversion targeted at a specific program element.

iv. The satellite development program will provide technology innovation funding to outside laboratories.

v. Innovative ideas for new systems will be actively encouraged by an appropriate reward structure.

d. Satellite development responds to surveillance requirements and interacts with the infrastructure program on control and data delivery issues.

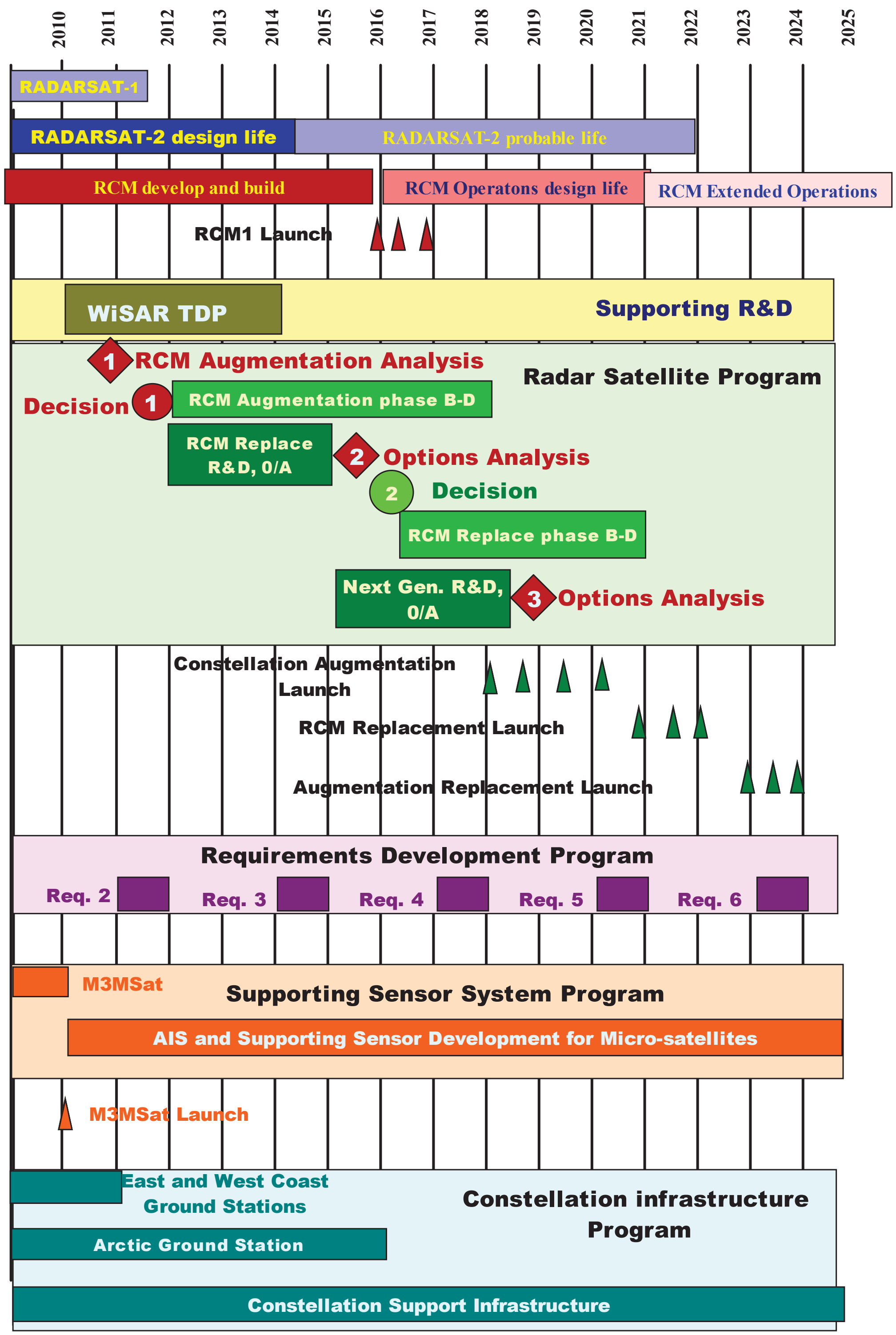

Figure 2: Notional constellation program model.

3. A constellation infrastructure program is developed and integrated with the requirements and satellite development programs.
    a. The constellation infrastructure program contains and / or manages the ground system components of the constellation. The program relies on a flexible interaction between government and industrial components to:
        i. develop, maintain and upgrade data reception stations;
        ii. maintain and evolve the ground communications infrastructure back-bone;
        iii. develop, maintain and upgrade telemetry and control stations;
        iv. develop, maintain and upgrade constellation tasking processes and technology; and
        v. develop, maintain and evolve data ordering, delivery and archiving systems.
    b. The constellation infrastructure program interacts with the satellite development program in matters of spacecraft control, diagnostics, on-orbit maintenance, tasking and data delivery.
    c. The constellation infrastructure has baseline funding for routine operations and acquires Treasury Board funding for major expenses.
    d. The constellation infrastructure program is responsive to innovations that improve its performance and provides appropriate reward structures to encourage this.
4. A supporting space sensor program is developed to augment the primary functions of the surveillance constellation satellites.
    a. The supporting space sensor program relies on R&D to develop and explore systems and sensor sets that can be combined with, or integrated into, radar satellite constellations to meet requirements that cannot be satisfied by radar sensors only.
    b. At present, supporting sensor development has been based on sequences of individual projects arising from the R&D community. It may be advisable to create a program structure to expedite development of successful candidates.

The four programs each have defined areas of responsibilities but are closely linked. There is a need for an oversight body whose members are senior government officials, perhaps at the ADM level, and whose responsibility is the effective coordination of the parts. The oversight group would have the power and mandate to influence the programs in such a manner that the global risk vs. cost curves jointly lay near the bottom of the multi-dimensional risk-cost bathtub. A major challenge for the oversight group is to exercise its mandate in a manner that is open to innovation while minimizing bureaucratic burden.

Implicit in this four program approach to the development, maintenance and operation of a Canadian radar surveillance constellation is the existence of government, academic and industrial R&D capability that can easily feed innovative ideas into the capability development process and can effectively interact with the constellation programs to help resolve technical problems that arise. Current bureaucratic roadblocks to effective integration of government, industrial and academic capabilities and expertise need to be minimized.

A notional, high-level roadmap timeline is shown in Figure 2. This figure is not complete in that it does not cover the full 20 year timeline referred to in the text nor does it include all parallel processes that must be synchronized with system builds. Although the primary focus is space-based radar system development, an auxiliary space-based ocean surveillance sensor that observes AIS transmissions from ships has been included to emphasize the mixed-type nature (in this case active and passive radio-frequency systems) of effective surveillance constellations.

One element that is evident in the depiction of the radar satellite design program is that the existing options analysis decision cycle used by CSA is episodic in nature and is designed around a project model that either builds large satellites or builds batches of similar satellites. In a true spiral development model, the decision cycle needs to be coupled with a continuously evolving plan for future capability and needs to be coupled to a new way of looking at satellite development phases. If this can be done effectively in a manner that jointly minimizes risk and bureaucratic overhead, the program based approach could provide a very effective alternative to the current way of doing business.

6.1.1 Surveillance radar requirements development program

The DND surveillance radar requirements development program is based on a spiral development model that expands desired CF surveillance capability outcomes into requirement sets suitable for space-based radar surveillance operations. The desired surveillance capability outcomes originate from the CFD Capability Planning and Capability Management Sense domain organizations within DND and from equivalent offices in other government departments. From the requirements definition point of view, DND has expressed the desired outcome:

“DND/CF has the ability to employ and integrate space capabilities into full spectrum operations,”

which can be partitioned into the following broad instructions:

1. Provide an enhanced ability to conduct surveillance of Canada’s territories, air and maritime approaches, including the Arctic, and anywhere in the world where CF/DND has an interest.
2. Provide an enhanced ability to efficiently and effectively achieve common or shared situational awareness of Canada’s territories, air and maritime approaches, including the Arctic, and anywhere in the world where CF/DND has an interest.
3. Provide an enhanced ability to efficiently and effectively plan, optimize and task collections of sensors and sensor function mixes for cost-effective accomplishment of ISR missions.

These instructions can be used to identify missions that can benefit from space-based surveillance which, in turn, identify desired surveillance capabilities. In the present model, desired surveillance capabilities are expanded into surveillance requirements within an organization such as DG Space (DG Space will be assigned this job in the model). The surveillance requirement set will be parsed by priority, timeline and existing capability to define the requirements to be met by the next spiral of constellation development. The requirement development process will have a nominal cycle time of three years. A notional surveillance requirement development cycle could take the form illustrated in Figure 3.

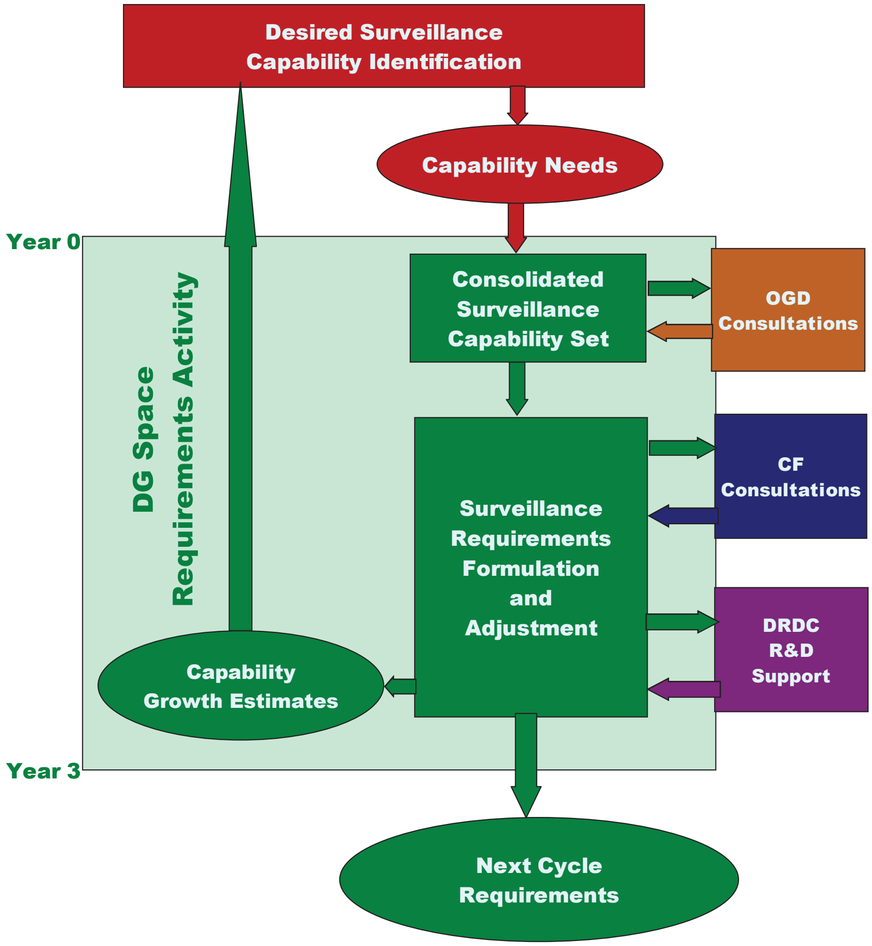

Figure 3: Notional surveillance requirement development cycle.

The actual desired surveillance capability set that drives the requirements development cycles will evolve over time as CF and OGD missions and responsibilities grow and shift.

6.1.2 Space segment development program model

When radar spacecraft are designed in the context of a radar satellite constellation, the single satellite design and implementation program model in Figure 4 needs to be changed to address the reality of the relationship between a satellite and the constellation that it works in. In the surveillance constellation model, the entity being created is the surveillance constellation and any satellite in that constellation is a temporary resident that is inserted, used, and removed.

Following the ideas outlined in Figure 2, the vision behind a viable surveillance constellation is to create a requirements driven, continuous-flow development and launch of surveillance constellation satellites. The surveillance satellite output rate will depend on the size of the surveillance constellation and the design lifetime of constellation member satellites. The challenge is to define a program that minimizes the annual cost of developing and maintaining a surveillance tool that consists of a constellation of surveillance spacecraft and the space-segment infrastructure needed to support and maintain it.

The continuous-flow output approach, Figure 5, offers several possibilities for cost control for a continuously changing output product.

1. A long-term, regular launch requirement schedule becomes a powerful bargaining tool for launch availability guarantees and launch cost.
2. A long term, regular build cycle becomes a powerful bargaining tool to minimize component and subsystem costs and to obtain adapted subs system interfaces. (long term market for standard parts and market for component innovations).
3. Continuous flow production (one or more units per year) allows assembly, integration and test (AI&T) facilities and procedures to evolve continuously instead of being custom built for each system.

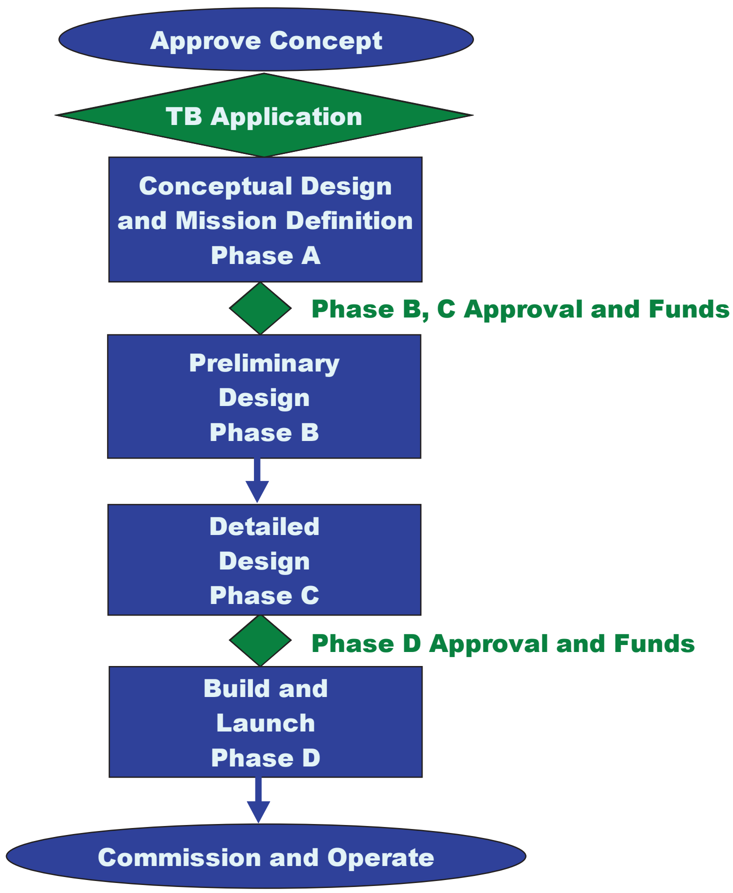

Figure 4: Single satellite development process used in Canada.

Accepting that a form of continuous flow satellite development and launch is feasible and can be implemented, there is a cyclic background of required activities associated with evolving, successive families of constellation spacecraft. In this context, a family of spacecraft is defined as a small group of radar constellation members (three or four units) that belong to the same design paradigm but may vary in function or implemented operational modes from unit to unit and are launched sequentially. Figure 4 is a notional representation of the radar spacecraft development model for radar constellation satellites.

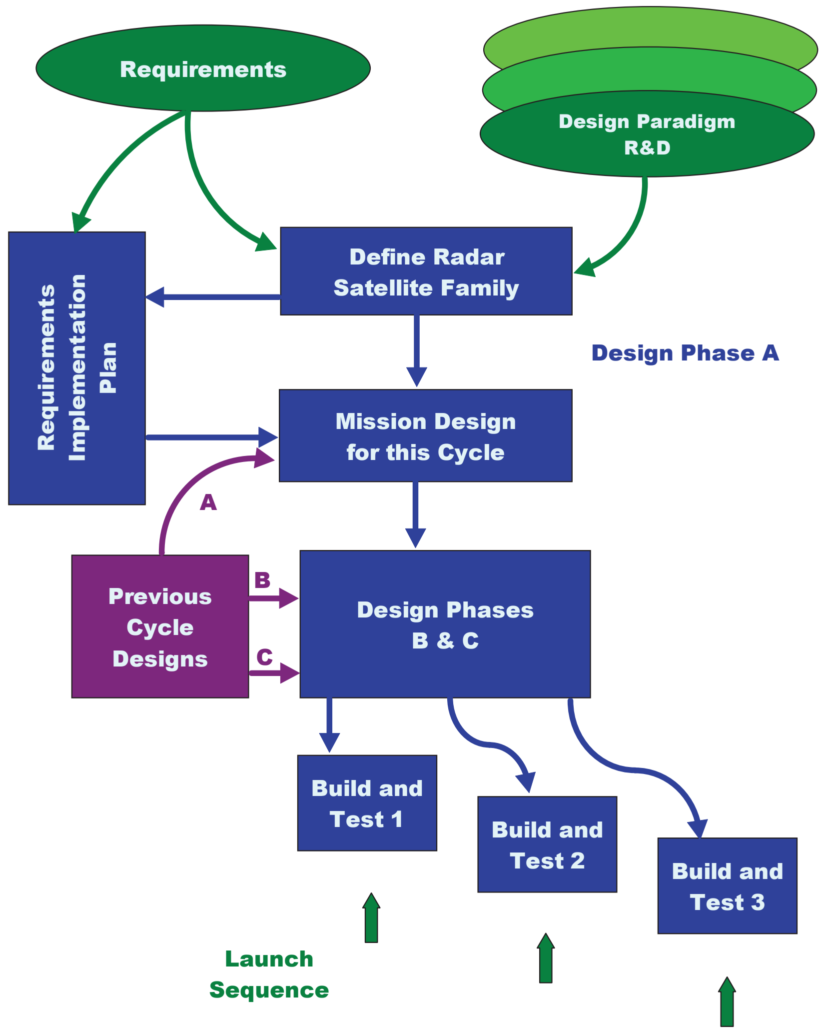

Figure 5: Notional description of one constellation spacecraft development and launch cycle.

When Figures 4 and 5 are compared it becomes evident that the development process for constellation satellites is quite different than that used for single satellites or even the first spiral of constellation development. For single satellites, the development process has taken up to a decade and each new system is an entirely new process that uses mostly or entirely new technology.

For the maintenance, expansion and evolution of a surveillance constellation:

1. Surveillance requirements are updated regularly and will normally exceed existing surveillance capability.
2. An ongoing process to develop, evolve and approve a requirements implementation plan will be required.
3. New technologies and system design paradigms will be continuously available from external R&D for inclusion in successive implementation cycles. Innovation must be encouraged to maintain international competitiveness for surveillance resource access trades.

4. Two or more time-staggered development processes (phases A to C) will be active at the same time. Successive cycles must overlap in time to accommodate the satellite build, test, launch and commissioning flow needed to sustain a surveillance constellation and incrementally meet its operating requirements.
5. Technologies and lessons learned from previous cycles will be sufficiently current that they can be used to shorten and strengthen active development phases. Mechanisms need to be developed to ensure that these are not locked in proprietary vaults.
6. There are cost and efficiency advantages to maintaining and incrementally upgrading personnel and physical resources instead of starting everything fresh each time.
7. The contracting models used to develop space systems will need to be revised.
8. Financing models and management structures based on a surveillance satellite development cycle and continuous-flow satellite development and launch will need to be developed.
9. Reliable and responsive satellite deorbit capabilities need to be included in each spacecraft to maintain access to constellation orbit slots as spacecraft age and are replaced.
10. Dedicated de-orbiting vehicles (space tugs) may be required to extract and dispose of non-responsive satellites.

6.1.3 Surveillance constellation ground segment program model

Up to and including the present time the ground systems that have been created to operate radar surveillance satellites have built organizations and physical facilities that are designed to meet the needs of the defined system for a limited period of time. For surveillance constellations whose effective lifetimes can exceed 20 years, the ground segments will need to evolve over time. Upgrade and reconfiguration processes must be built into the ground segment design concept so that the total system performance can meet expectations over the constellation life. A constant flow of available process and technology enhancements is expected, and operational lessons-learned need to be captured and used. A ground segment renewal cycle for processes and facilities must be built into the top-level planning and resource allocation activities.

6.1.3.1 Operating a surveillance radar constellation

Canadian experience in operating both nationally and commercially owned radar satellites has provided some excellent operations models that can be applied to the process of operating a surveillance radar constellation. International experience in operating small radar satellite constellations exists in Germany and Italy.

When a sensor system such as RADARSAT-2 is replaced by a constellation of sensors, the constellation becomes the entity that is tasked to perform surveillance functions and a constellation management system needs to be established to task and schedule the individual constellation satellites. Figure 6 illustrates a notional, high-level, constellation operation model.

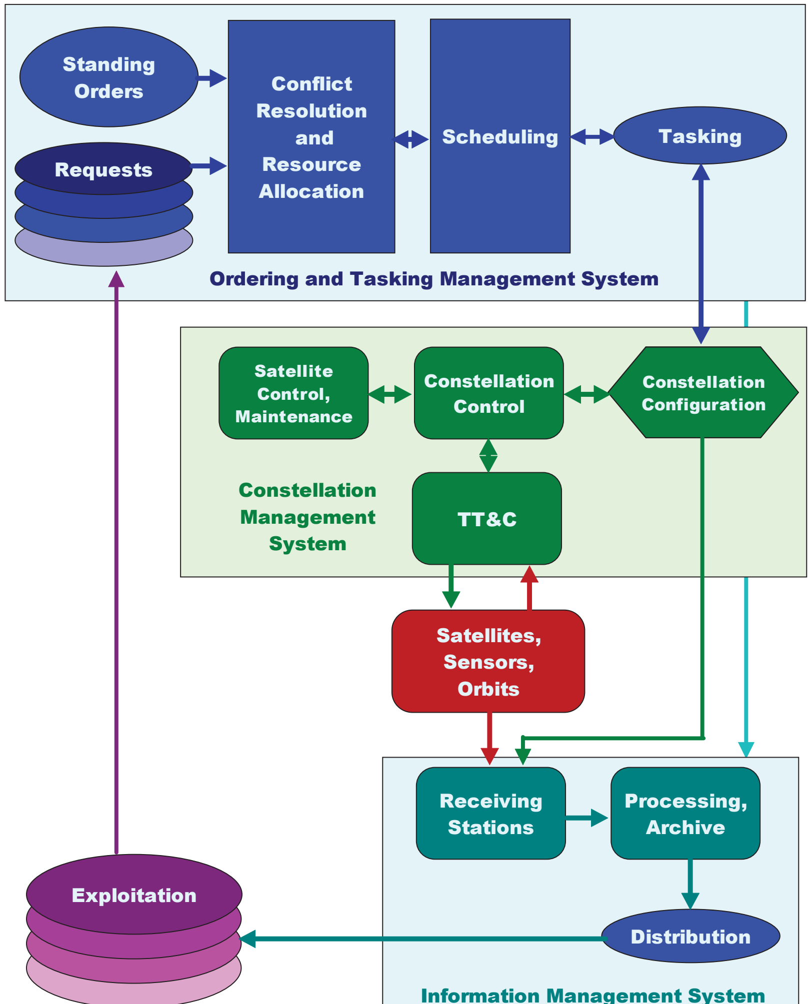

Figure 6: Notional high-level overview of constellation ground segment operation.

6.1.3.1.1 Ordering, tasking and management system

The ordering and tasking management system in Figure 5 is similar in form and context to the order management system currently in use. It contains:

1. Order desks;
   The order desks are interactive web-connected interfaces that allow user agencies to:
   a. specify surveillance tasks,
   b. set task priorities,
   c. manage internal user conflicts,
   d. obtain feedback on submitted requests.
2. An order tacking system;
   The order tracking system monitors the progress of surveillance requests through to their execution of rejection. It:
   a. generates tracking data,

    b. retains a status data base,
    c. identifies and triages delivery issues,
    d. connects products generated to requesting agency and provides deliver instructions.
3. A conflict resolution system;
    a. maintains a data base of constellation configurations and schedules,
        - The available constellation configurations will include scheduled satellite down-time needed for calibration, configuration, and maintenance activities.
    b. identifies conflicts between incoming and scheduled surveillance requests,
    c. resolves conflicts through dialogue with requesting agencies or through specified priority ranking,
    d. outputs surveillance tasks to be executed.
4. A scheduling and acquisition management system;
    a. determines surveillance task schedules,
    b. acts on high-priority, rapid response requests and flags such interrupts to the conflict resolution system;
5. Constellation tasking;
    a. issues and tracks constellation surveillance tasks.
6. Interfaces to:
    a. The information management system.
       The information management system needs to know:
        - which reception stations are assigned to which request,
        - the processing and delivery priority for each request,
        - the data delivery path for each request.

       The ordering and tasking management system needs to know:
        - the status of all reception and processing sites,
        - the communication link status for all links,
        - the data processing and delivery status, and
        - the archive contents and access index.
    b. The constellation management system,
       The constellation management system needs to know:
        - the surveillance tasks and task schedules,
        - data receiving station assignments, and
        - the status of data back-haul communications links.

       The ordering and tasking management system needs to know:
        - the constellation status including the status of individual satellites,
        - the TT&C status, and
        - the current and planned satellite task assignments.

Current satellite ordering and acquisition management systems use web-based technologies to automate functions described in this section as much as is currently possible. Some decision points require human intelligence and every effort has been made to make these as responsive as possible. In today's world, fast response translates to acquisition within twelve hours of a request. Existing models provide a good starting point for constellation operations. Depending on the constellation form, constellation response to emergency surveillance requests can be much faster that signal satellite response and the ordering and tasking system delays need to be adapted to this reality. There are several challenges that will need to be addressed.

6.1.3.1.2 Constellation management system

The constellation management system outlined in Figure 6:

1. accepts surveillance tasking orders from the ordering and tasking system,
2. defines the constellation configuration (individual satellite tasking) needed to conduct the surveillance tasks according to the defined schedule,
3. monitors and maintains each satellite in the constellation;
4. conducts calibration operations and maintains calibration data;
5. manages satellite orbits;
6. sets satellite configurations schedules, modes, beams and configurations;
7. communicates commands to the constellation members and receives data from the member satellites, and
8. makes decisions on constellation member replacement requirements.

At the present time, satellites such as RADARSAT-2 require a team of professionals to execute the functions above for a single system. Several innovations will be needed to execute these functions for a surveillance constellation. These will include the development of automated and semi-automatic, interactive, tools to minimize human activities where this is possible and desirable. The constellation configuration role is a completely new activity.

An effective model for the constellation management system needs to be created. International approaches to this problem may provide some lessons-learned to start the process. The problem of establishing an adequate network of automated TT&C stations needs to be addressed. Secure web-based communications will be required.

6.1.3.2 Information management system

The information management system outlined in Figure 6:

1. Contains a web-connected network of automated receiving stations that:
    a. receive, unpacks and quality check satellite data transmissions,
    b. send received data sets to one or more processing centers.
2. Contains one or more data processing centers that:
    a. decrypt, unpack and quality-check incoming data;
    b. generate data products suitable for information extraction;
    c. archive raw data;
    d. transmit processed data to an information dissemination facility.
3. Contains an information dissemination facility that:
    a. packages data sets for dissemination;
    b. may provide some information extraction operations for routine surveillance operations.
    c. supplies data and/or information products to surveillance requestors.

Several different, working versions of the information management system are in service world-wide. The adaptation of these to a Canadian radar surveillance constellation is a matter of expanded scale and increased automation. Secure, web-based communications will be necessary.

6.1.3.3 Operations centers

The notional constellation ground-segment model outlined in Figure 6 does not explicitly contain a GoC operations centers block. It is implicitly assumed that many of these exist, are the sources of information requests, are the recipients of processed data and/or pre-extracted information sets, and are the information extraction centers that exploit surveillance information

6.2 Straw-man roadmap summary

Section 6 provides a notional vision for the implementation of a Canadian radar surveillance constellation in the form of a straw-man implementation model. This section is intended to provoke discussion about how to realize the basic concept and identifies a set of issues to be addressed. It is hoped that discussions arising from the vision presented here will result in a better model for Canadian surveillance constellation implementation and will result in a viable action plan.

The highlights of the model are:

1. The surveillance constellation is a long-lived entity whose satellites are short-lived parts of the whole and evolve over time.
    a. There is a background R&D effort that evolves the functionality of constellation members.
    b. The constellation is tasked as an entity and constellation management decides on resource allocation to each task.
    c. The constellation is government owned and controlled.
2. The development, maintenance and functional growth of the constellation are best executed as a program rather than a series of individual projects.
    a. Issue: a program mandate is required.
    b. A continuous flow model for satellite development, deployment and decommissioning is advantageous.
        i. There are contracting process implications.
        ii. There are governance implications.
        iii. There are financing implications.
    c. A continuous requirements generation and refinement process guides constellation use and the development of its members.
        i. It is recommended that DND provides guidance and implementation and that other government departments interface with the DND process.
        ii. Requirements generation is either a component of the surveillance constellation program or is a tightly-linked, parallel program.
    d. A continuing and evolving ground segment manages the constellation operation, tasking, data management, information extraction, information storage and information dissemination processes.
        i. There is a background R&D effort that evolves the ground segment capabilities
        ii. The ground segment design permits controlled, continuous upgrade.
3. Notional models are provided for the space segment, requirements generation and ground segment parts of the constellation program.

7 Summary comments

This document expresses the author's vision for the development of a Canadian space-based surveillance system-of-systems based on the concept of a long-lived constellation of radar surveillance satellites. The document is intended to be a tool that provokes discussion within DND and other Government Departments leading to a well considered space-based surveillance plan.

The document has been organized as follows:

1. Section 1 presents background information and presents a vision for Canadian space-based radar surveillance evolution.
2. Section 2 discusses a sub-set of GoC surveillance requirements that can be addressed by radar surveillance satellites. The list, that is presented in this section samples the surveillance requirements of a few Canadian Government departments, and is not complete. Reference [2] emphasizes that requirements spring from 23 legislative acts governing the responsibilities and actions of 21 government departments and agencies. The main point is that there is no consolidated set of GoC surveillance requirements. The draft set of DND surveillance and reconnaissance requirements in Annex A is identified as a model that needs to be expanded across the GoC.
3. Section 3 summarizes international space-based radar surveillance systems that are either on orbit or will be soon. The section discusses the possibility of a multi-nation surveillance constellation and of augmenting Canadian space assets with international resources.
4. Section 4 introduces the idea of a long-lived Canadian space-based radar surveillance constellation from a system-of-systems point of view and discusses some of the implications of and some of the issues surrounding this approach.
5. Section 5 discusses a procurement process strategy needed to implement the ideas presented in section 4 and identifies some issues that need to be addressed.
6. Section 6 presents a straw-man plan for the development of a Canadian surveillance capability that is based on a long-lived surveillance satellite constellation. A program approach to implementation is suggested and the problem is decomposed into a set of related and interacting programs. High-level, conceptual models of each program are presented to provide foci for detailed analyses and discussion.

Each section ends with a summary that provides a high-level overview of the points made in that section.

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Annex A Draft DND surveillance requirements for space-based radar constellation definition.

Starting in December 2008, the DND D Space D (now DG Space) organization has been developing a set of surveillance requirements[2] to guide DND space-based surveillance capability development. At the top level, this work flows from DND strategy documents and is summarized in the CF/DND desired outcome statement:

"DND/CF has the ability to employ and integrate space capabilities into full spectrum operations."

The requirements set that has been developed remains in draft form but is being used to define Canadian surveillance satellite development for the next generation of RADARSAT constellation satellites.

Although this requirement set is DND-centric, it has been reviewed by representatives from Canadian government departments who used space-based observations and has been found to be compatible with their present needs. The draft DND space-based surveillance requirements are summarized in Table A-1.

Table A-1: Summary of draft DND surveillance requirements

Number	Type	Description	Repeat
DND 0100	Canadian domestic maritime area	Detect all ships with length 25 m and larger within 1200 nm of the coast in sea state 5 or lower and provide speed and course estimates.	4 times daily
DND 0110	Canadian Expeditionary maritime task group	Detect all ships with length 25 m and larger within a 250 nm radius circle in sea state 5 or lower and provide speed and course estimates.	4 times daily
DND 0120	Continental North American Maritime area	Detect all ships with length 25 m and larger within 1200 nm of the coastal area surrounding North America in sea state 5 or lower and provide speed and course estimates.	Two times daily
DND 0130	UK-Norway Maritime area	Detect all ships with length 25 m and larger within 1200 nm of the European coast	Once daily

[2] The initial version of the D Space D surveillance requirement set was compiled by LCDR Andrew Samoluk for Col. Francis Malo and current refinements of the requirement set are being conducted by Maj. Richard Ladouceur working under the direction of Col. Andre Dupuis.

		(including the strain of Gibraltar, the White Sea and the Mediterranean Sea) in sea state 5 or lower and provide speed and course estimates.	
DND 0140	Canada-Australia Coalition Maritime area	Detect all ships with length 25 m and larger within 1200 nm of the Australian coast in sea state 5 or lower and provide speed and course estimates.	Once daily
DND 0200	Persistent Vessel Detection	Detect, identify and track all vessels, day and night, in all weather conditions, in near real time.	
DND 0210	SAR/AIS coverage rate	Complete SAR/AIS coverage for monitored maritime areas.	4 times daily
DND 0230	AIS Signal Detection	Class A vessel AIS messages must be received and discriminated with 90% probability.	
DND 0240	AIS coverage area	AIS coverage should be at least the SAR coverage area. World-wide is desired	
DND 0250	SAR/AIS data latency	Data latency should not exceed 15 minutes from the sensor observation time	
DND 0300	Tactical Land Reconnaissance	Monitor up to 100 10 km x 10 km scenes world- wide at high resolution (1 m x 1 m or finer) and detect coherent changes.	4 day coherent repeat, 2 days is desirable
DND 0310	Operational land Reconnaissance	Monitor up to 20 100 km x 100 km areas world- wide at medium resolution (5 m x 5 m) and detect coherent changes.	4 day coherent repeat, 2 days is desirable
DND 0400	High resolution imagery	Provide resolution of 0.5 m or finer for spot observations.	
DND 0410	Moving target indication	Determine the velocity and direction of targets moving on land or water.	
DND 0500	Global revisit	It must be possible to revisit world-wide targets at least every 12 hours.	
DND 0600	Time Sensitive Tasking	The surveillance constellation must be able to receive, process, and execute changes to the	

		collection plan in real time, constrained only by the command station position.	
DND 0610	Emergency Override	The surveillance constellation must have a non-routine capability to override non-DND orders for emergency or security purposes.	
DND 0620	Download to Deployed Ground Stations	It must be possible to download SAR and AIS data to ground stations deployed in expeditionary operations.	
DND 0630	System Protection Measures	The constellation system must provide robust protection for commands and data links in accordance with GoC security policies.	
DND 0640	Unrestricted Data Policy	It must be possible to share any data product with any partner of coalition without restriction.	

A review of the DND draft requirement set suggests that it is not complete (there are no polarization or radar frequency sensitive elements although R&D results suggest that these may be significant) and that there will be other requirements forthcoming in the future. Specific requirements that relate to the surveillance and remote sensing activities for other government departments are absent but may be covered by the DND requirements.

From the point of view of the design of Canadian surveillance satellite constellations, the existing requirement list is indicative and valuable but is incomplete.

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List of symbols/abbreviations/acronyms/initialisms

ADM	Assistant Deputy Minister
AIS	Automatic Identification System
AI&T	Assembly, Integration and Test
AOI	Area of Interest
C4ISR	Command, Control, Communications, Computing, Intelligence Surveillance and Reconnaissance
CF	Canadian Forces
CIS	Canadian Ice Service
COP	Common Operating Picture
COSI	COrea SAR Instrument
CSA	Canadian Space Agency
CSG	Cosmo Second Generation
DEM	Digital Elevation Model
DFAIT	Department of Foreign Affairs and International Trade
DG	Director General
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
D Space D	Directorate of Space Development
ESA	European Space Agency
GMTI	Ground Moving Target Indication
GoC	Government of Canada
HH, HV, VV, VH	Transmit linear polarization-receive linear polarization combinations
HRTI	High Resolution Terrain Information
IGS	Information Gathering System
ISR	Intelligence, Surveillance and Reconnaissance
MDA	McDonald Dettwiler and Associates
NORAD	North American Aerospace Defense Command

OGD	Other Government Departments
R&D	Research & Development
RCM	RADARSAT Constellation Mission
RFP	Request for Proposal
RNG	RADARSAT Next Generation constellation
RSSSA	Remote Sensing Space Systems Act
SAOCOM	Satellites for Observation and Communications
SAR	Synthetic Aperture Radar
TB	Treasury Board
TT&C	Telemetry, Telecommunication and Control

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With the advent of the Canadian RADARSAT Constellation Mission, the Canadian Space Agency has embarked on a transition from the use of individual radar surveillance satellites, represented by RADARSAT-1 and RADARSAT-2, to the use of a radar satellite constellation to perform radar surveillance observations. The transition from single satellites to satellite constellations drives some major changes in the way in which space-based surveillance radars are developed and operated and some equally major changes in the way in which surveillance measurements are tasked, retrieved and used. The use of constellations of radar surveillance satellites is a completely new way of doing business and raises many issues that will need to be addressed. This document presents the author's opinion on many of the issues that will need to be addressed as Canada evolves its surveillance capabilities and makes suggestions about work that will be required if one (or more) constellation(s) of Canadian spacecraft is a viable, long-term surveillance solution.

This note is written as a discussion paper that presents a vision of a possible way for Canada to develop and use a space-based surveillance radar constellation to provide a straw-man starting point for concept development and implementation. It is intended to trigger discussions about the development and implementation of Canadian Government space-based surveillance resources and their uses.

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