Canadian Institute for International Peace and Security

Institut canadien pour la paix et la sécurité internationales

WORKING PAPER 31

SURVEILLANCE OVER CANADA

by

George Lindsey
and
Gordon Sharpe

December 1990

WORKING PAPER 31

SURVEILLANCE OVER CANADA

by

George Lindsey
and
Gordon Sharpe

December 1990

For more copies, please write:

360 Albert Street, Suite 900
Ottawa, Ontario
K1R 7X7

ISBN 0-662-18352-5
CC 293-5/31E

PREFACE

Working Papers, the results of research work in progress or a summary of a conference, are regarded by the Institute to be of immediate value for distribution in limited numbers -- mostly to specialists in the field. Unlike all other Institute publications, these papers are published only in the original language.

The opinions contained in the papers are those of the participants and do not necessarily represent the views of the Institute and its Board of Directors.

Colonel Gordon Sharpe was a research fellow at the Canadian Institute for International Peace and Security (CIIPS) in 1989-90, and is currently the Director of Doctrine Coordination and Development at National Defence Headquarters. All views and analyses presented in this paper are based on information available from public sources, and do not necessarily represent the perspectives and opinions of the Department of National Defence.

Dr. George Lindsey is a visiting senior research fellow at CIIPS, and was formerly the Director of the Department of National Defence Operational Research and Analysis Establishment (ORAE).

Acknowledgements

In the course of the research for this project the authors were accorded valuable consultations with representatives of MacDonald Dettwiler (in particular Mr. Murray MacDonald), Spar Aerospace Limited (in particular Dr. F.J.F. Osborne), and Canadian NORAD Region (in particular the Commander, Major General J.D. O'Blenis). They also wish to acknowledge the constructive criticism of the editorial staff at CIIPS, and the benefits of the space indoctrination course provided by the Canadian Forces School of Aerospace Studies, commanded by LCol. David Peart, and the assistance of Mr. Dan Labay also of CFSAS.

PREFACE

Working Papers, the results of research work in progress or a summary of a conference, are regarded by the Institute to be of immediate value for distribution in limited numbers – mostly to specialists in the field. Unlike all other Institute publications, these papers are published only in the original language.

The opinions contained in the papers are those of the participants and do not necessarily represent the views of the Institute and its Board of Directors.

Colonel Gordon Sharpe was a research fellow at the Canadian Institute for International Peace and Security (CIIPS) in 1989-90, and is currently the Director of Doctrine Coordination and Development at National Defence Headquarters. All views and analyses presented in this paper are based on information available from public sources, and do not necessarily represent the perspectives and opinions of the Department of National Defence.

*

Dr. George Lindsey is a visiting senior research fellow at CIIPS, and was formerly the Director of the Department of National Defence Operational Research and Analysis Establishment (ORAE).

Acknowledgements

In the course of the research for this project the authors were accorded valuable consultations with representatives of MacDonald Dettwiler (in particular Mr. Murray MacDonald), Spar Aerospace Limited (in particular Dr. F.J.F. Osborne), and Canadian NORAD Region (in particular the Commander, Major General J.D. O'Blenis). They also wish to acknowledge the constructive criticism of the editorial staff at CIIPS, and the benefits of the space indoctrination course provided by the Canadian Forces School of Aerospace Studies, commanded by LCol. David Peart, and the assistance of Mr. Dan Laney also of CFSAS.

CONDENSÉ

Au cours de la prochaine décennie, le Canada devra de diverses façons exercer une surveillance sur toute une gamme d'activités menées dans ses vastes régions peu peuplées et dans leurs approches. Les nouvelles techniques offrent désormais de remarquables possibilités pour la surveillance. Au Canada, il n'existe pas de grands programmes scientifiques et technologiques qui accroîtraient la compétitivité de notre pays sur ces deux plans, sur la scène internationale. Vu la transformation récente de la conjoncture stratégique mondiale, on pense qu'il faudra modifier les rôles et la structure des Forces canadiennes.

Les auteurs du présent *Document de travail* tentent d'établir une corrélation entre ces quatre facteurs. Ils décrivent les besoins du Canada, tant civils que militaires, en matière de surveillance, ainsi que les capacités et les limites des techniques modernes de surveillance. Ils étudient les problèmes à résoudre pour structurer les forces armées de manière qu'elles puissent se charger de fonctions nationales en période de détente internationale, tout en demeurant à même d'assumer leur rôle militaire de dissuasion, de se déployer dans des régions troublées, ou de prendre de l'expansion si la tension internationale venait à s'accroître.

La technologie de la surveillance dépend des capteurs et des plates-formes. Grâce aux techniques modernes de traitement des transmissions, la résolution des images radars s'améliore constamment. Les radars à ouverture synthétique donnent une résolution de quelques mètres dans le cas d'objets stationnaires à la surface de la planète, et ce, même depuis des centaines de kilomètres de distance. Grâce à un radar d'un autre type, on peut détecter et suivre un aéronef en vol, même si on l'observe d'une altitude élevée et que la toile de fond est la Terre. Malheureusement, il n'est pas encore possible de combiner ces deux fonctions en un seul satellite ou avion, ce qui permettrait de suivre des objets en déplacement et d'obtenir rapidement des images très détaillées des secteurs voulus de la Terre.

Des capteurs électro-optiques modernes, fonctionnant dans le spectre de la lumière visible et de l'infra-rouge, produisent des images d'une très haute résolution révélant de nombreux détails d'objets à la surface de la terre; ils sont aussi capables d'exploiter les différences de température et la réflexion de la lumière. Ils sont cependant gênés par les éléments obscurcissants, tels que les nuages, la pluie, la brume, le brouillard ou la poussière.

Les satellites permettent de couvrir très rapidement de vastes régions de la Terre, car ils se déplacent environ trente fois plus vite qu'un avion; ils sont par ailleurs capables de balayer un corridor plus large. En revanche, ils ne passent qu'un faible pourcentage de leur temps au-dessus du Canada; il est très difficile d'en modifier l'orbite, et il est en général impossible de les réparer en cas de panne. Ils coûtent très cher, et il n'est pas rentable d'en restreindre l'emploi à la surveillance d'une partie limitée de la Terre, quand ils passent inévitablement la majeure partie de leur temps au-dessus d'autres régions. Avec les techniques classiques de production d'électricité, l'alimentation électrique des capteurs perfectionnés pose un problème.

Les avions ne peuvent atteindre les altitudes des satellites, mais ils sont en mesure de survoler longtemps les secteurs présentant de l'intérêt aux fins de la surveillance; en outre, on peut les diriger à volonté. Des êtres humains les pilotent, et il existe au sol des installations pour les entretenir et les réparer quand ils atterrissent. Un avion coûte beaucoup moins cher qu'un satellite, mais il en faudrait beaucoup pour couvrir la zone correspondante que balaierait un satellite survolant un pays aussi vaste que le Canada.

Des contraintes importantes limitent les capacités des stations terrestres employées pour surveiller une grande zone à la surface de la planète, ou une activité menée dans l'atmosphère au-dessus de ladite zone. Il existe une exception : le radar transhorizon, qui peut surveiller les mouvements des aéronefs dans une très grande zone. Cependant, son rendement faiblit à proximité de la zone aurorale, dont une grande partie est située au-dessus du territoire canadien.

En ce qui concerne la défense contre les missiles ou les avions, les besoins du Canada s'apparentent énormément à ceux des États-Unis. On s'attend à ce que ces derniers continuent à surveiller l'espace. Les aéronefs susceptibles de menacer l'Amérique du Nord s'en approcheront très vraisemblablement via le Nord canadien, et il faut donc continuer à exercer une surveillance efficace sur les corridors d'approche, afin de pouvoir donner l'alerte tôt, le cas échéant. Pour assurer une défense active, il faudrait être à même de suivre les mouvements des aéronefs et des missiles de croisière air-sol partout au Canada. Cela nécessiterait de nombreuses installations, bien plus complexes que ce dont nous disposons actuellement, et seule une constellation de satellites permettrait d'y arriver. Pareil réseau offrirait cependant un avantage secondaire très intéressant pour le contrôle de la circulation aérienne civile au-dessus des régions où il est insuffisant ou inexistant aujourd'hui.

Si nos forces armées sont chargées de surveiller les mouvements des aéronefs au-dessus du Canada et de ses approches, la même infrastructure devrait pouvoir s'occuper du contrôle de la circulation civile, surveiller les mers (notamment pour protéger les zones de pêche), mener des opérations de recherche et de sauvetage après des accidents survenus sur terre, en mer ou dans les airs, et contribuer à la lutte contre l'importation illégale de narcotiques.

Tout dépendant des caractéristiques des capteurs, il devrait également être possible d'obtenir de l'information pour diverses fins, dont les prévisions météorologiques, la surveillance des glaces, des forêts, des cultures, des feux de forêt et des inondations, l'établissement des cartes marines, et la détection de la pollution de l'air et des eaux.

Il est aussi possible que les moyens de surveillance permettant de suivre les mouvements d'aéronefs au-dessus du Canada, ou de navires dans les eaux canadiennes, ou encore de fournir des images de haute qualité d'activités au sol, s'avèrent utiles pour la vérification du respect des accords de maîtrise des armements et dans le cadre des opérations de maintien de la paix dans d'autres parties du monde. Les satellites couvrant le Canada survolent aussi le reste du monde; les avions peuvent être envoyés n'importe où; et il serait possible de transférer ailleurs, grâce aux Forces canadiennes, l'organisation et les compétences nécessaires pour faire fonctionner de tels systèmes chez nous.

Avant de formuler des recommandations éclairées sur les grandes décisions à prendre relativement à la politique et aux programmes canadiens de surveillance aérospatiale, il faudra se renseigner à fond sur les besoins, les avantages et les coûts, et s'interroger sur les possibilités de coopération. En un premier temps, le présent *Document de travail* esquisse ce qui est sans doute possible, sur le plan physique.

EXECUTIVE SUMMARY

During the coming decade Canada will have a growing need for several types of surveillance over a variety of activities throughout her vast and largely uninhabited area and the approaches thereto. Evolving technology is providing remarkable new capabilities for surveillance. Canadian science and technology lack major programmes that would make her more competitive on the international scene. Recent changes in the international strategic situation suggest changes in the roles and structure of Canada's armed forces.

This paper attempts to link these four factors. It outlines Canadian needs for surveillance, both for defence and for civilian purposes, and the capabilities and limitations of modern surveillance technology. It discusses the problems of structuring the armed forces to be useful for national functions in a period of international detente, but to be able to continue to perform their military role of deterrence and to be ready for deployment to troubled areas, or for expansion in the event of increased international tension.

Surveillance technology depends on sensors and on platforms. Modern signal processing technology is allowing better and better resolution of radar images. Synthetic aperture radar permits resolution of a few metres for images of stationary objects on the earth's surface, even at ranges of hundreds of kilometres. A different type of radar permits the detection and tracking of aircraft in flight, even when observed from high altitude against the background of the earth. Unfortunately it is not yet possible to combine in a single satellite or aircraft system these two modes of operation, to provide both rapid imaging of areas of the ground in great detail, and the tracking of moving objects.

Modern electro-optical sensors, operating at visual and infrared wavelengths, produce images of very high resolution able to distinguish many details of objects on the surface of the earth, and able to make use of temperature differences as well as reflection of light. They are, however, limited in their ability to operate through obscurant such as cloud, rain, fog, haze, or dust.

Orbiting satellite platforms allow very rapid coverage of large areas of the earth, moving at about thirty times the speed of an aircraft, and usually able to overlook a wider swath. However, they cannot spend more than a few percent of their time over Canada, are very restricted in their ability to alter their orbit, and are usually impossible to repair in the event of a failure. They are very expensive, and it is inefficient to restrict their employment to the surveillance of a limited portion of the earth when they inevitably spend most of their time over other regions. Provision of electrical power adequate for advanced sensors is a problem for conventional power generating technology.

Aircraft cannot reach the altitudes of satellites, but can spend most of their flying time over areas of interest for surveillance, and can be redirected at will. They have human operators aloft, and facilities for maintenance and repair when they land. One aircraft is much cheaper than one satellite, but a considerable number would be needed to match the coverage of one satellite over an area as large as Canada.

Stations on the ground are severely limited in their ability to provide surveillance of a large area of the surface of the earth or of activity in the atmosphere above it. An exception is Over-the Horizon radar, which is able to provide very wide area surveillance of the movements of aircraft. However, its performance is degraded in the vicinity of the auroral zone, much of which is situated over Canadian territory.

The needs for defence of Canada against attack by missiles or aircraft are virtually the same as those for the United States. It is expected that surveillance of space will continue to be conducted by the USA. Aircraft threatening North America are very likely to make their approach over Northern Canada, and there is a need for continuous effective surveillance over the approach routes in order to provide early warning of such activity. To conduct active defence it would be necessary to be able to track the progress of aircraft or air-launched cruise missiles across Canada. This would require extensive facilities, far beyond anything in place at this time, and could only be provided by a constellation of satellites. However, such a system would offer a very valuable side benefit for the control of civilian air traffic over regions where it is ineffective or unavailable today.

If the Canadian Armed Forces are charged with surveillance over the movements of aircraft over Canada and its approaches, the same organization and equipment should be able to conduct civilian air traffic control, monitor the sea for such purposes as fisheries protection, carry out search and rescue after accidents on land, sea, or air, and contribute to surveillance over the illegal importation of drugs.

Depending on the sensors, it should also be possible to provide information for many purposes such as weather prediction, ice reconnaissance, marine charting, monitoring the state of forests and agricultural crops, spread of forest fires or floods, and the detection of air and water pollution.

It is also possible that surveillance able to follow the movement of aircraft over Canada, or ships in Canadian waters, or able to produce high quality imagery of activity on the ground, would find a useful role in the verification of arms control agreements and in peacekeeping activities in other parts of the world. Satellites in orbits covering Canada go everywhere else, aircraft can be sent anywhere, and the organization and skills necessary to operate such systems in Canada could be transferred elsewhere by the Canadian Armed Forces.

Before responsible recommendations can be made regarding major decisions for Canadian aerospace surveillance policy and programmes it will be necessary to investigate needs, benefits, and costs in detail, and to examine the possibilities of international cooperation. This working paper as a first step, outlines what may be physically possible.

TABLE OF CONTENTS

ANNEXES

FIGURES

TABLES

INTRODUCTION

At the present time Canada lacks definitive long-term plans in several areas of national importance which are changing rapidly, and for which inaction could lose valuable opportunities, or, at worst, be extremely damaging during the next ten to fifteen years.

One of these areas is national defence. The current welcome atmosphere of superpower detente and disarmament should allow substantial reductions in a number of defence activities. But a government responsible for the long-term security of its citizens must face the possibility that troubles may arise in the future, for which disciplined, well-trained, and adequately equipped armed forces will be needed. What is required today is a plan for the Canadian Department of National Defence that will give it the capability to keep up with military technology as it develops in future years, and to be able to expand rapidly should the need arise.

Another field of change is the widespread growth in the use of high technology in many areas, civilian as well as military. Industrial competition is and will continue to reward those nations able to master and exploit technology, and to penalize those that fail to do so. Already Canada is falling behind many other countries in the developed world.

Associated with both of these questions is the need for a country to be able to observe what is going on within its own territory. In Canada's case, the territory is immense, most of it is sparsely inhabited, and beyond the central land mass. There are extensive regions over which surveillance has been impossible in the past, but will become increasingly more desirable in the future.

Recent advances in the technologies of sensors and of space vehicles offer opportunities for Canada to address all three of these above-mentioned problems, provided that we act in time. Surveillance is needed for defence, and modern technology is making it feasible to provide a degree of surveillance over Canada and its surrounding approaches far beyond anything heretofore possible. Once provided for the purposes of defence, surveillance will be able to make valuable contributions to many other services of national importance. And experience gained in the development of the necessary equipment, and in its operation, will keep Canada abreast of one of the most promising fields of rapidly expanding high technology.

Consequently, this paper is addressed to the need for surveillance over Canadian territory and the approaches to it, the means by which this might be achieved, the benefits that it would bring, and the role that should be played by the Canadian Armed Forces.

The subject has immense scope. Surveillance incorporates high technology, the most advanced in the world today and being advanced further at an extraordinary pace. In order to comprehend what is possible now, and what is expected to be possible a few years hence, it is necessary to understand the major features of modern sensor technology and the capabilities and limitations of earth satellites, as well as those of the more familiar aircraft and ground stations. Fortunately, although the precise designs of the most advanced sensors and vehicles are protected by military and commercial secrecy, the principles and general physical characteristics are readily understandable. The principal objective of this paper is to outline the most important and relevant technical features of the sensors and vehicles that could be available in the future for the various applications of surveillance over Canada.

Before responsible recommendations can be made regarding major decisions for Canadian policy and programmes it will be necessary to know not only what is technically possible, but also how much of it Canada needs, how much it would cost, what benefits would accrue to the nation beyond those conferred directly by good surveillance, and what would be the likely international implications. After this will come questions such as whether to carry out the programme nationally or in cooperation with other countries, how much of the equipment should be developed and built in Canada and how much bought abroad, and what would be the implications for the future of science and engineering in Canada. Apportionment of the tasks among government and industry, and among the departments of the Canadian government will have to be determined.

With so many stages in the entire process, this CIIPS working paper concentrates on the first: to discuss what is and what soon may be technically possible, and what useful results could be produced for Canada. Touched on more briefly are questions of the particular role for the Department of National Defence. At this stage it is inappropriate to offer more than a few speculative remarks regarding costs or international implications. Those and the other factors are left for further studies.

PART I - FUTURE CANADIAN NEEDS FOR SURVEILLANCE

Meeting Future Surveillance Needs for Defence

For security against foreign aggression a nation needs to be able to detect the approach of missiles, of uninvited military aircraft and naval vessels, and of ground forces configured for invasion.

In the case of Canada, geography and the cooperation of allied nations make seaborne invasion impractical, and warning of such a highly improbable operation virtually certain. But security requires effective surveillance of the approach of ballistic and cruise missiles, of bomber and maritime patrol aircraft, of naval surface ships, and submarines. Also needed is the capability to track missiles and unidentified aircraft over Canadian territory, and to observe suspect activities in remote locations on the ground or nearby ice pack.

In an age of detente, it may be acceptable to relax the level of continual surveillance. But partial disarmament, including substantial reductions in the numbers of intercontinental nuclear weapons, makes the preservation of stable strategic deterrence more, rather than less, dependent on reliable warning of attack. The probability that a surprise counterforce attack could succeed in disarming the victim of the strategic weapons that would have enabled him to retaliate becomes greater as the number of strategic weapons is reduced.

In the event of a crisis, it is important to minimize the temptation to preempt, or to launch on warning that could be inaccurate. This danger becomes much less acute if both adversaries feel confident that warning of attack will be assured and prompt, and that they will be able to take practical steps to reduce their vulnerability. These steps could include launching of aircraft needed to duplicate ground-based command, control and communications systems. Some of the strategic bomber aircraft could take off, not for attack but to ensure that they survive. Therefore, the capability to conduct reliable surveillance must be preserved.

The opinion may be offered that under present circumstances there is no danger of intercontinental attack, and the expense of maintaining surveillance would be unjustified. But the present circumstances may change, and the capability for hideous destruction still exists. Surely the importance of preserving stability and making certain that the hideous destruction never occurs justifies the continuation of the surveillance that has so far required no more than a very modest proportion of the expenses borne for the (successful) prevention of a nuclear war.

Geography has placed Canada in a part of the world in which certain vital parts of the surveillance function must be carried out. But a major part of the cost of conducting the surveillance in Canada has been borne by the United States.

Detection and Tracking of Missiles and Aircraft

Strategic deterrence is provided for Canada by the intercontinental nuclear weapons based in the United States, but the routes along which these weapons and the facilities for their command and control could be threatened lie over the Arctic, over Canada, and along the Atlantic and Pacific coasts of North America. Figure 1 shows two sample ground tracks of ballistic missiles launched from fields in the USSR towards strategic targets in the United States. These would be detected by satellites and by the ground-based Ballistic Early Warning (BMEWS) stations in Alaska, Greenland, and England, unless they had been jammed or destroyed. Also shown are three possible routes for strategic bomber aircraft. These may divert from great circle routes in order to avoid or delay detection by radar, and they may release air-launched cruise missiles to fly the last few thousand kilometres to their targets, using their own built-in guidance. A few illustrative air-launched cruise missile tracks are shown on Figure 1.

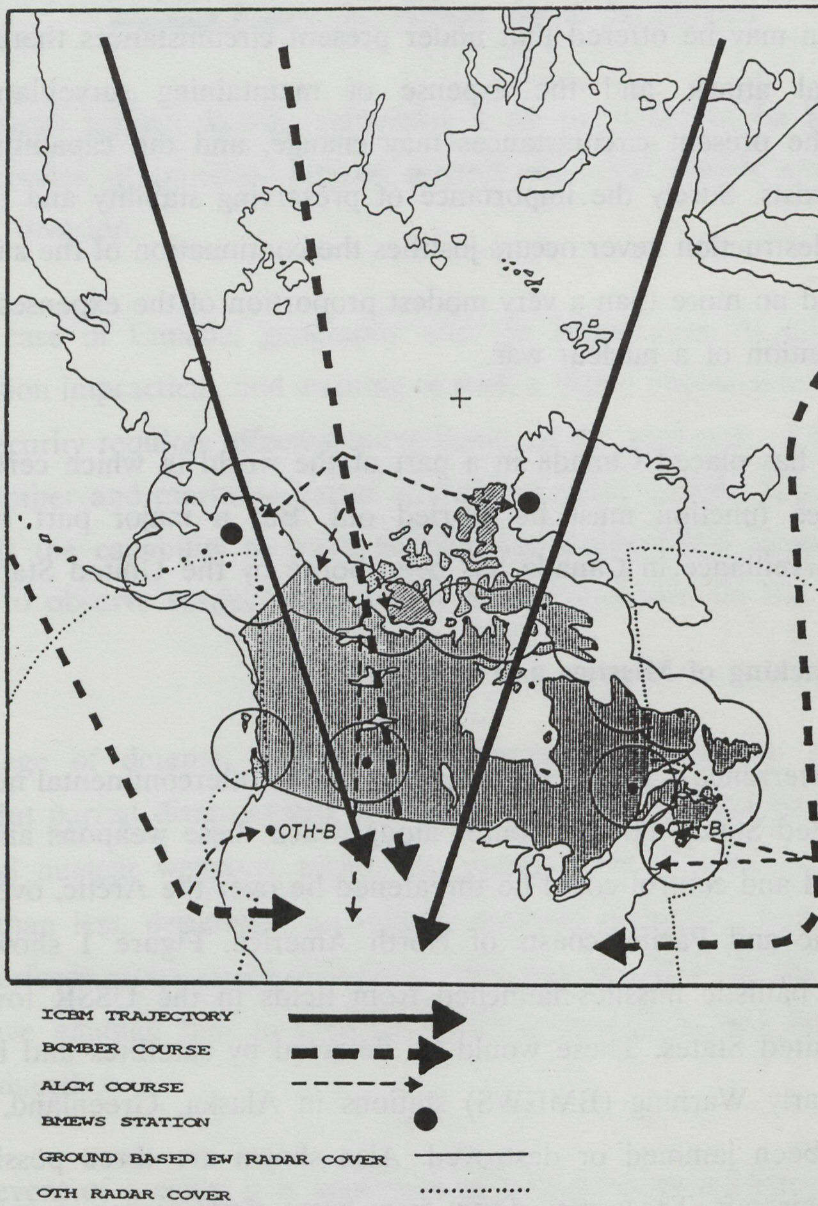

Figure 1
AIR AND MISSILE APPROACHES

Except for the occasional patrol by airborne warning and control (AWACS) aircraft, or the fortuitous presence of a warship, the systems to detect bombers are all ground based. The Over-the-Horizon (OTH) radars cover sectors shaped like a pineapple slice, surveying large areas of the North Atlantic and North Pacific Oceans (see Figure 1), but these cannot function in the Arctic, because of auroral activity, or at ranges inside a "dead zone" extending out to about 800 km from the installations, because of the angles of reflection from the ionosphere.

Conventional radars sited along the Atlantic and Pacific coasts will detect high altitude bombers at ranges of 300 km or so, but far less if they are flying low. Across the northern edge of the Alaskan and Canadian mainland there is the North Warning System, consisting of a single line of radars able to detect aircraft at virtually any altitude, but unable to track their progress once they pass the single line.

AWACS aircraft can be flown to patrol a considerable area north or south of the North Warning System, or off the coasts, but there are not enough of these to provide any continuous coverage.[1] Fighter aircraft can be sent to intercept a target being tracked by radar, but which has not been identified by comparison with flight plans or by radio communication. For this purpose Canada has established Forward Operating Locations (FOLs) at bases in the Arctic close to the North Warning System radar line.[2]

---

[1] "USAF, NATO Invest Heavily in AWACS Electronic Upgrade," *Aviation Week & Space Technology*, 1 January 1990: p. 45. This article states that 34 AWACS aircraft are assigned to the United States where they are under control of the Tactical Air Command. A limited number of these may be assigned to NORAD.

James W. Canan, "The Big Hole in NORAD," *Air Force Magazine*, October 1989, p. 57. The Commander of NORAD is quoted, regarding the number of AWACS required to provide twenty-four hour surveillance of the Persian Gulf: "... we would need ten AWACS aircraft, some tankers, and very large crews for maintenance and so forth."

[2] *Challenge and Commitment, A Defence Policy for Canada,* Ottawa: Ministry of Supply and Services, 1987. pp. 55 - 57.

Supplemented by radars in the southern Atlantic and Pacific coasts of the USA for the purpose of detecting submarine-launched ballistic missiles, these detection systems have been adequate for the early warning requirements of the 1980s. But three developments threaten their effectiveness in future years.

One of these is the land-attack cruise missile, launched from aircraft, submarine, or surface ship. Much smaller than a long-range aircraft, and able to fly long distances at very low altitude, it offers a very difficult target for ground-based radar. It is believed that the range of Soviet ALCMs is or will soon be sufficient for them to be launched outside of the radar cover of the North Warning System and still reach most of the strategic targets in North America.[3]

A second development detrimental to surveillance is stealth technology, used to reduce the echo reflected from a pulse of radar energy. Stealth can be applied to an aircraft or cruise missile, and possibly to a ballistic missile. Stealth has applications against electro-optical detection as well, taking forms such as camouflage, infrared decoy flares, cooling of engine exhausts, and coatings to reduce infrared emission.[4]

The third development is electronic warfare, increasingly able to jam or deceive radar, or to guide a missile to home on a radar transmitter. A ground-based radar is a vulnerable target for a stealthy homing cruise missile, which would probably destroy the radar without having been detected.

Against low-flying aircraft or cruise missiles the fundamental limitation posed for conventional ground-based radars by the line of sight is so severe as to disqualify them

---

[3] "Specifications of Soviet Missiles," *Aviation Week & Space Technology*, 19 March 1990: p. 162. This source credits the AS-15 Kent, the new air-launched cruise missile carried by the Soviet Bear-H and Blackjack strategic bombers with a range of 1,850 miles (or 2,977 kilometres).

[4] George Lindsey, *The Tactical and Strategic Significance of Stealth Technology*, Quebec: Dossiers Series - CQRI, 1989.

as a long-term solution for surveillance of any substantial area. Their difficulties are compounded by stealth technology, especially in view of the fact that the radar will see an approaching low-flying cruise missile almost head-on, the worst aspect for early detection. But sited in an aircraft or space vehicle, not only will a radar have a clear line of sight to long range, but it will see the cruise missile from above, presenting a much bigger target and one much more difficult to conceal by stealth. Moreover, airborne infrared sensors can be used to detect the heat from the exhaust of the cruise missile's engine, provided that the line of sight is not obscured by cloud. And an aircraft or satellite is less vulnerable to jamming than a facility in a known fixed location.

Over-the-horizon radar has two advantages over ground-based microwave radar, and may be able to detect cruise missiles at long range.[5] The small, low target will return more energy upwards in the direction of the reflected path from the ionosphere than it would in the direct head-on aspect seen from a line-of-sight radar at ground level. And the longer wavelength may resonate with the wings or fuselage of the missile, which would produce an enhanced reflection.

While initial detection followed by identification constitute the most vital functions of surveillance, it would also be desirable to be able to track the subsequent movement of missiles, aircraft, submarines, or ships after they have been identified and warning achieved. BMEWS does this for ballistic missiles, but unless AWACS happens to be in the right place at the right time, or an interceptor is in contact, surveillance of the track of an aircraft or cruise missile is lost as soon as it passes out of the cover of the North Warning System.

Initial detection and identification provide the crucial early warning needed to alert the leadership and reduce the vulnerability of the retaliatory forces. The value of

---

[5] "Maine OTH-B Completes Tests; GE to transfer system to USAF," *Aviation Week & Space Technology,* 9 April 1990, p. 52. This article mentions that the Maine radar has seen cruise missiles, but that it would be extremely expensive to enhance this capability.

subsequent tracking would be to confirm the nature of the attack, and to allow active and passive defence to function, provided that the means were in place.

There are many major differences between the systems needed to provide warning of attack and those with a capability for active defence. If the warning system functions as intended, then it has fulfilled its mission once warning is delivered, whether or not the system is destroyed in the attack. With the possible exception of cleverly designed covert incapacitation of the functioning of sensors, attack of the warning system should provide the desired warning.

But the early part of an attack may be directed against key components of the defences, with the intention of rendering the defence ineffective. Radars needed for the tracking of bombers or missiles, operations centres needed for the direction of the defences, and interceptor aircraft and anti-aircraft weapons intended for the destruction of the attackers may be targeted by bombs and missiles, degraded by electronic countermeasures, and possibly subjected to electromagnetic pulses from nuclear explosions.

Motivated by the difficulty of intercepting ICBMs, Canada and the United States have placed primary reliance for the protection of the North American continent on strategic nuclear deterrence rather than on active defence. Consequently, in the consideration of the various needs and means for surveillance over the continent and the approaches to it, priority should be given to effectiveness prior to attack, rather than to vulnerability if attack should occur.

A major advantage of space-based sensors would be their potential for detection of aircraft far to the north of the North Warning System, before cruise missiles had been launched, and for tracking of both aircraft and missiles as they made their way across Canada. It is, however, highly probable that it would require more satellites to provide continuous tracking north and south of the North Warning System (or some other line established as the "boundary for warning") than simply to produce a high probability of detection at that boundary.

Detection and Tracking of Submarines and Surface Ships

Although it would be possible for submarines to launch ballistic missiles against North American targets from positions close to the Canadian coast, there seems little reason for them to do this. The ballistic missiles carried by modern Soviet submarines have sufficient range to reach the strategic targets in North America, even if they are launched from areas close to the coast of the USSR, where they can take cover under ice, park in shallow water, and have the benefit of antisubmarine defence from nearby bases.

However, there are missions for which other types of Soviet submarines would have to come out of their own waters. The most important would be for attack of NATO shipping in the North Atlantic or along the Pacific coast, whether at sea or by mining the approaches to the seaports. Another would be to threaten the egress of American submarines and surface ships from their home bases in the Atlantic and Pacific. A third mission would be to launch cruise missiles against land targets (in North America and Western Europe). In each case, the shortest routes from the great naval bases in the Kola Peninsula into the North Atlantic are through the Greenland-Iceland-United Kingdom gap (the GIUK gap), between Greenland and Iceland or between Iceland and Scotland, as shown on Figure 2. But NATO can concentrate antisubmarine defences on the gap, and would be likely to detect the passage of any significant number of submarines (or surface ships or aircraft). If surprise were desired, the submarines might use other routes from the Kola into the North Atlantic through Davis Strait between Greenland and Canada, or through passages between the islands of the Canadian Archipelago (several of which can be traversed by submarines even when covered by floating ice).[6] The reason for Soviet submarines to transit right across the Arctic Ocean could be for exchange between the fleet based in the Kola and the one in the Pacific.

---

[6]G.R. Lindsey, "Strategic Stability in the Arctic", *Adelphi Paper 241*, International Institute for Strategic Studies, London, 1989. pp. 39-44. *Challenge and Commitment*, p. 52.

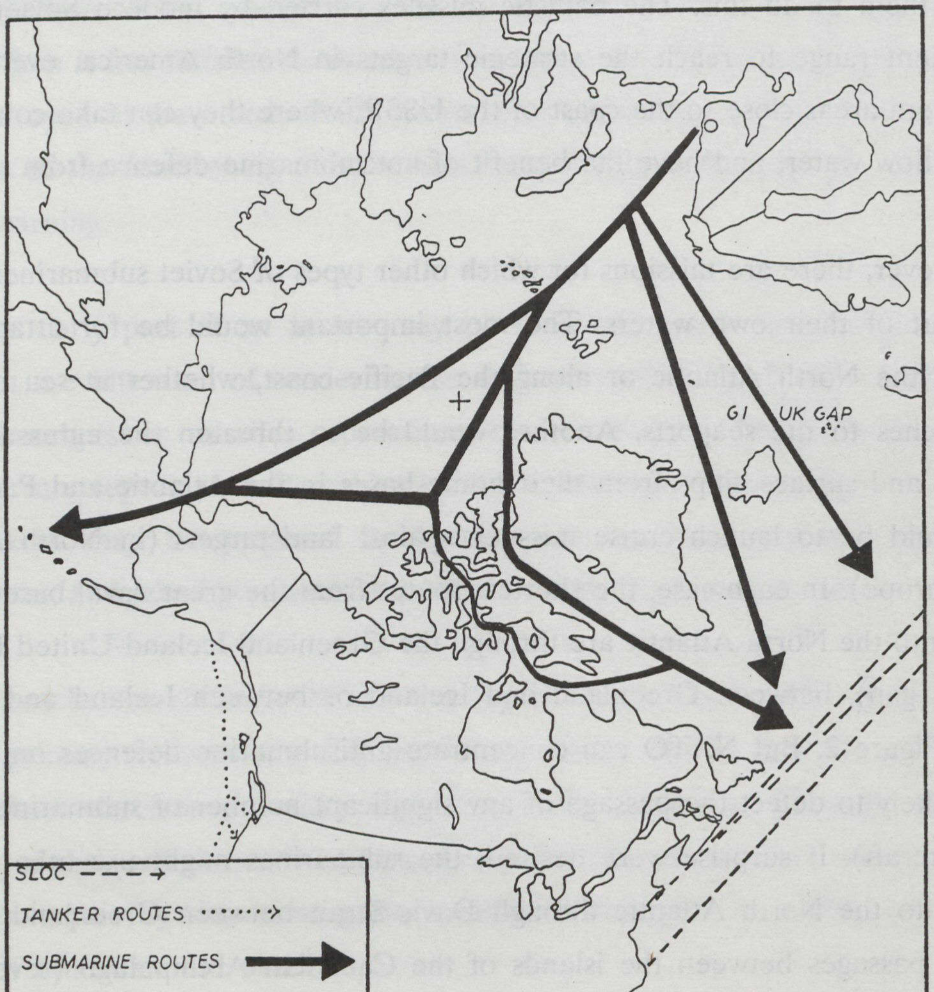

Figure 2

POSSIBLE SOVIET SUBMARINE ROUTES

For Canada, the need for the surveillance of submarines presents three quite different aspects. In the Atlantic, it is related to the protection of shipping between North America and Europe (indicated by the dashed lines on Figure 2, which follow great circle routes to Europe). In the Arctic, it is concerned with detection of passage of attack submarines through the Canadian Archipelago. In the Pacific, the two principal problems are protection of shipping through the strait between Vancouver Island and Washington State, including that of US strategic submarines from the great base in Bangor, and of tanker traffic from Alaska to Western Canada and the Pacific coast of the continental USA.

This paper is concerned with surveillance from space, air and ground of the approaches to and the territory of Canada, and can make no more than passing reference to the important problems of surveillance of underwater activity. The most effective instrument for surveillance of surface ships is the maritime patrol aircraft, equipped with radar. Although difficult in the open ocean, surveillance of submarines is best carried out by bottom-mounted passive sonar, backed up by maritime patrol aircraft equipped with sonobuoys. Canada's Aurora aircraft are very effective for surveillance of both surface ships and submarines, but eighteen aircraft are insufficient to perform adequate surveillance in three oceans, especially when they are often diverted for other tasks.

For surveillance of the passages through the Canadian Archipelago, ice cover makes aircraft of very limited use for initial detection. What is needed here is the construction of sonar barriers across a few narrow passages, selected for their physical characteristics and so that passage from the Arctic Ocean into the North Atlantic must cross at least one of them. Failing the provision of submarines capable of operating under the ice, prosecution of contacts made by Canadian sonar in the Arctic would have to be performed by United States nuclear-powered submarines, except for instances in which open water would allow employment of aircraft equipped with sonobuoys.

Space vehicles are unlikely to play a major part in antisubmarine surveillance, except for their role in communications and navigation. They could be important for the relay of signals from floating sonobuoys, including fields of long-life moored buoys, and communications to and from submerged submarines.

Surveillance for Verification and Peacekeeping

Although this study is aimed at the needs for surveillance over Canadian territory and its approaches, aircraft and satellites able to perform surveillance over this part of the world could be used elsewhere as well. In fact, it is a basic characteristic of a satellite that it cannot help overflying all of the earth's surface between the latitudes set by the inclination of its orbit. It must return its information to earth via a ground readout station, but if some delay is tolerable the data can be stored until the satellite comes into the line of sight of a readout station in home territory. A possible restriction could be presented by limitations of electrical power, should this be insufficient to maintain operation of the equipment over a large part of the orbit. In this case, surveillance over home territory might have to be suspended during the orbits used for distant surveillance. Similarly, aircraft useful for surveillance over Canada could be sent elsewhere.

The recent increase in interest over arms control is due in no small part to the improved prospects of verifying compliance with the undertakings agreed. These prospects are due to an improved climate for cooperation, but also in part to the rapidly developing capabilities of satellites and aircraft to monitor the types of activity that would signal the breaking of the terms of an arms control treaty. Studies of the potential use of observation satellites have been made by France, which suggested the creation of an International Satellite Monitoring Agency,[7] by Canada, which has examined the possibility of using satellites to monitor activity in space (PAXSAT A),[8] or on the ground (PAXSAT

---

[7] "An International Arms Control Monitoring Agency," *SIPRI Yearbook, 1980* pp. 187 - 188. During the 1978 United Nations General Assembly Special session on Disarmament France proposed the formation of an International Satellite Monitoring Agency.

[8] SPAR Aerospace Limited, *PAXSAT A, A Study of the Feasibility of a Spacecraft Based System to Determine the Presence of Weapons in Space*, Ottawa: November 1984.

B),[9] and by Sweden, which has studied the prospects for a multinational satellite for the verification of an agreement to reduce multinational forces in Europe.[10]

Another activity related to security and defence, one in which Canada has played a prominent part, is that of peacekeeping. For peacekeeping to be effective it is necessary to maintain close surveillance over the activities of the parties in conflict, although the peacekeepers may not be allowed to visit these parties at close quarters. Under such circumstances, the type of surveillance provided by aircraft or satellites could be of great value, and it is also possible that use could be made of helicopters, balloons, dirigibles, or unmanned aerial vehicles (UAVs).[11]

To be useful for either arms control verification or peacekeeping, the reception and analysis of the information should be performed by an international organization located close to the region of interest, which is unlikely to be in North America. But there is no technical reason why a satellite or aircraft designed for surveillance over Canada could not be employed for one of these other roles as well, for example by reporting its information to the international organization.

The technical demands of surveillance for arms control or peacekeeping would not be as severe as for North American defence, but probably more severe than for most of the needs for civil purposes, to be discussed later. For peacekeeping in some underdeveloped areas it would be extremely useful to be able to construct accurate large

---

[9] External Affairs, Canada, *PAXSAT Concept, The Application of Space-Based Remote Sensing for Arms Control Verification*, Verification Brochure No. 2, Ottawa: undated. This report concentrated on the ground in central Europe.

[10] Commercial and third party satellites. Chapter 3, by Johnny Skorve, in *Verification of Conventional Arms Control in Europe: Technological Constraints and Opportunities*, eds. Richard Kokoski and Sergey Koulik. SIPRI, Westview Press, Boulder, 1990, pp. 68-73.

[11] External Affairs, Canada, *Overhead Remote Sensing for United Nations Peacekeeping*, Ottawa: April 1990. This report provides an excellent overview of important considerations, sensors, platforms, costs and structures applicable to this role.

scale maps. Surveillance would not have to be continuous, and it would not be essential to detect or track the flights of missiles or aircraft. Some delay in reporting would be tolerable. But it would be necessary to obtain imagery with high resolution, making it possible to distinguish tanks from trucks, for example, and to identify certain types of weapon systems. For surveillance, useful results could be expected from thermal imaging systems mounted in low speed aircraft flying at low altitudes.

Civil Peacetime Value of Aerospace Surveillance of Aircraft and Surface Ships

Among the responsibilities of a sovereign nation are measures to ensure safety of navigation at sea and in the air. Safe navigation at sea requires accurate charts, including depth soundings in shallow water. Once made, most charts have a long useful life, but in some waters the combinations of current and deposits of silt cause the depths to change, requiring charts to be amended (or dredging conducted). Although soundings can be taken by a ship with a fathometer at any depth, it is now possible to survey shallow bottoms by laser sensors[12] operating from an aircraft or satellite.

Ice is a hazard to navigation in the Arctic, the northwest Atlantic, and on the Great Lakes. It is now normal practice for icebreakers to use light helicopters to reconnoitre the ice in their vicinity, but more extensive surveys can be done by airborne or spaceborne radar, passive radiometry, or photography. Oil drilling and production platforms can be endangered by icebergs, and if sufficient warning is provided they can be towed out of danger.

Navigation both at sea and in the air relies on weather forecasts, which are becoming ever more dependent on satellite observation, especially over the oceans and

[12] "Navy, DARPA Study Lasers to Detect Soviet Submarines" *Defense News*, 11 September 1989, p. 14.

in the more remote regions where there are few land-based meteorological reporting stations. Oil rigs can take precautions in advance of major storms.

When major accidents occur, at sea or in the air, the responsibility for search and rescue extends beyond the sovereign territory of a state. In the case of Canada, it covers large areas in the Pacific, Arctic, and Atlantic Oceans, indicated on Figure 3. An important contribution to efficient search and rescue has been made by SARSAT, a satellite system able to receive signals from an emergency location transmitter (ELT) carried by aircraft and ships. The ELT can be activated by hand or by the deceleration of a crash landing, and a satellite will record its bearing. However, rapid rescue could be expedited if surveillance had been following the course of an aircraft and could produce an accurate estimate as to its last known position, particularly in the event that the ELT is destroyed, malfunctions, or the transmission is blocked by terrain.

In the vicinity of seaports and airports, where it is most congested, sea and air traffic is surveyed and controlled by ground-based radar. But off-shore, and over most of the land area of Canada, ships and aircraft proceed without surveillance. Instructions are given as to the routes and altitudes to be adopted by aircraft, but often deviations are made, either unintentionally or sometimes on purpose.[13] Figure 3 shows the extent of air traffic control radar cover over Canada and the over-ocean areas that fall under Canadian responsibility. This assumes that the aircraft cooperates by use of a transponder beacon, which adds to the range and aids in identification. Continual tracking of air traffic would permit greater capacity, and contribute to the avoidance of accidents as well as to successful search and rescue following a crash.

---

[13] "Blind Over the Pond," *Aviation Week & Space Technology*, 23 April 1990, p. 15. Article quotes the Canadian Aviation Safety Board as reporting : "... gross navigational errors continue to create serious losses of separation and sometimes risk of collision over the North Atlantic." The situation is assessed to be partly a problem with the limits of coastal radars.

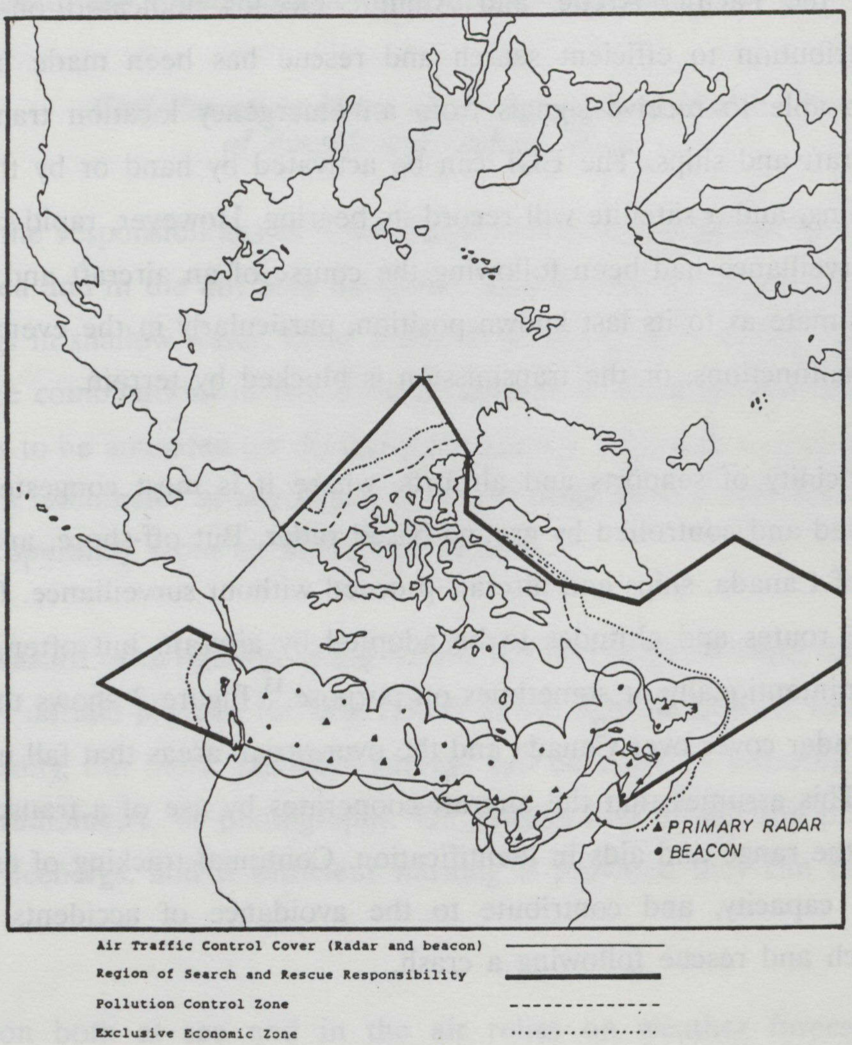

Figure 3
AIR TRAFFIC CONTROL COVERAGE AND ZONES OF RESPONSIBILITY

For preservation of strategic deterrence, the prime requirement is for reliable early warning of the approach of non-cooperating aircraft and cruise missiles coming from outside the North American continent. While desirable, the subsequent tracking of these objects is less important than their initial identification. In contrast, air traffic control needs nearly continuous tracking of cooperating aircraft, especially when they are approaching or flying in the most congested areas. The two requirements are not the same, and a system optimized for one function may not be adequate for the other.

As well as providing for the safe navigation of ships and aircraft, which will presumably cooperate with the system serving to increase their safety and efficiency, a nation must be able to detect and prevent illegal activities carried out by ships and aircraft within the area under national jurisdiction. In the case of ships, this includes illegal fishing, a practise of increasing seriousness off the Atlantic coast of Canada, where the depletion of fish stocks is causing severe economic hardship, and is likely to result in both local and international quarrels over the quotas to be taken and the division of those quotas. It is not impossible that Canada could find itself in a "Cod War", in which case the possession of ocean-going warships would be a significant asset. For regulation of fishing, Canadian jurisdiction extends 370 km from the coastal baseline, to the lines indicating the Exclusive Economic Zone on Figure 3.[14]

Other maritime transgressions against which surveillance is required are pollution, most often by discharges of oil near the coast, and smuggling, with the most serious contraband being narcotics. The Arctic waters pollution prevention act covers an area north of 60°N and 165 km beyond territorial waters.[15] This limit is illustrated in Figure 3.

---

[14] Sea Law Convention, 1982: Article 56 paragraph 1 states: "In the exclusive economic zone, the coastal State has (a) sovereign rights for the purpose of exploring and exploiting, conserving and managing the natural resources, whether living or non-living, of the waters ..."

[15] John Honderich, *Arctic Imperative, Is Canada Losing the North?* Toronto: University of Toronto Press, 1987, pp. 52 - 54.

International law is not yet agreed regarding national jurisdiction over the exploitation of minerals on the sea bed beyond the 370 km Exclusive Economic Zone. Some coastal states wish to have rights out to the edge of the continental shelf, or to the 210 metre depth contour. The Grand Banks off Newfoundland extend well beyond the Canadian EEZ. In addition to their fishing value, which is of major international importance, they may also offer the opportunity for extraction of oil or solid minerals from the seabed.

Most of the very large expanses of water, land and ice under Canadian functional jurisdiction are not under surveillance today. Surveillance is a necessary first step in prevention of law breaking, but must be followed up by interception and arrest. Identification and tracking of a suspected fish poacher, polluter or smuggler could be followed by subsequent inspection, and if necessary arrest, either at sea or after landing, a function for the civil authorities rather than the armed forces. Regulations could be instituted regarding large visible markings to be placed on ships in a manner making them identifiable to an airborne electro-optical sensor.

Aircraft play a significant transportation role for the narcotics trade, and as the United States becomes more successful in the prevention of imports from the south, one can anticipate an increase in efforts to penetrate Canada. The means to detect illegal air entry are not unlike those needed for military air defence, although for Canada it will be the southern rather than the northern approaches which need to be surveyed. The intruders will include small, slow aircraft, and identification will be more difficult. However, the objective will be arrest at the landing field rather than destruction in the air.

Other Civil Peacetime Services Available from Aerospace Surveillance

Mention has already been made of the value of aerospace surveillance for weather prediction, ice reconnaissance, and marine charting, which are of course needed for many civilian purposes. Indeed, accurate weather forecasting is of great value for agriculture, protection against hurricanes, planning of outdoor events, and many other activities. The major meteorological organizations are making effective use of satellite observations for these purposes. Map making includes updating to record growth of cities and changes to forested and agricultural areas, both eminently suited for observation with airborne or spaceborne electro-optical or radar sensors. Short-term changes of great importance to agriculture and forestry can be observed, providing valuable information concerning the progress of crops, rate of growth of trees, and incidence and spreading of forest fires. Flooding can be observed. Geological information can be obtained from overhead sensors which is useful for prospecting for minerals.

The increasing concern over deterioration of the environment is creating a demand for many types of monitoring of the atmosphere as well as the land and water. Sensors such as electro-optical multi-spectral scanners are able to detect quite small concentrations of particulate and gases in the air, or of chemicals on the surface of water.[16] What is lacking is a widespread network of sensors at different altitudes, such as could be provided by space vehicles and aircraft, perhaps carrying additional appropriate sensors in addition to those needed for the conduct of a primary role in security.

---

[16] National Oceanic and Atmospheric Administration, United States Department of Commerce and the National Aeronautics and Space Administration, *Space-Based Remote Sensing of the Earth, A report to the Congress*, Washington: September 1987, p. 66 and p. 74.

Geographic Characteristics of Canada and the Approaches to Canada

The geographic position of Canada with respect to its neighbours and surrounding oceans is badly represented on the most commonly used maps. The familiar Mercator projection, for example, suggests that Europe lies due east from Canada, and Asia due west, with nothing to the north except a swollen and distorted Greenland. A far better presentation is given by an azimuthal projection tangent at the north pole, or better still at a point near the centre of Canada. The maps in this paper use an oblique gnomonic projection which minimizes distortion in Canada, and depicts great circles, which form the shortest trajectories between any two points on the surface of the earth, as straight lines.

On a gnomonic map such as shown in Figure 1,[17] it is evident that the shortest routes for missiles or aircraft coming from the interior of the USSR to the United States lie across the Arctic Ocean, Alaska, Greenland, Iceland, and Canada. Surveillance against these threats to the United States and Canada must be carried out over these territories.

As described earlier, the protection of NATO's shipping in the North Atlantic requires surveillance of submarine movements in the Norwegian Sea and GIUK gap, and of certain passages through the Canadian Archipelago, as well as surveillance of the approaches to the seaports and shipping routes. In the Pacific, the only choke points are on the Asian coast, but two zones close to Canada that have strategic importance are the focal points outside the Juan de Fuca Straits, and the route down the west coast for oil tankers coming from Alaska.

Inside the outer boundaries of Canada there is a most uneven distribution of population and assets. The cities and most of the other settlements are concentrated close

---

[17] This gnomonic projection is tangent at 60°N latitude and 95°W longitude (very near Churchill, Manitoba). The scale and shape of geographic features are accurate at this point and become less so as distance from the point increases.

to the southern border with the United States. Vast regions in the centre and north, although potentially very rich in resources, are inhospitable and almost uninhabited. Strategically, one could class the southern strip of Canada 200 km wide and stretching from east to west along the United States border as the inhabited area, with the remaining 90% of the area nearly unoccupied territory[18] over which missiles and aircraft would have to fly in order to reach valuable strategic targets in Canada and the USA.

However, in spite of demographics, a central authority claiming sovereignty over all of this vast territory has an obligation for surveillance of activity, as well as for development of what may prove to be valuable resources. And, apart from considerations of security, which may not prove serious in the next few years, there are other responsibilities of government which extend beyond the land and territorial seas. These include search and rescue following maritime or air accidents, protection of environmental assets, including wild life in the Arctic, and policing of fishery and prospecting regulations. Thus, for civil as well as defence considerations there is need for extensive surveillance over very large areas of uninhabited and inhospitable territory. Some of these requirements represent international legal obligations, others are simply the normal responsibilities of a sovereign state.

[18] In fact, only 0.3% of the population of Canada, or approximately 77,000 people occupy the northern territories. The population density of the entire country is about 10% of the world average - 2.8 persons per square kilometre. Population figures extracted from the *Encyclopedia Britannica Book of the Year - 1990.*

PART II - THE TECHNICAL CHARACTERISTICS OF THE MEANS OF SURVEILLANCE

Capabilities and Limitations of Surveillance

Surveillance has always been a key factor in military operations. In ancient times it was limited to what could be seen with the human eye, perhaps from the top of a hill or the mast of a ship. More recently it became possible to enhance optical observation by field glasses or telescopes, and then by photography, and to elevate the observer (or camera) in a balloon. But these improvements could not overcome obscuration by darkness, fog, or rain.

The major technological advances that have improved the capabilities for surveillance during the present century are the ability to raise the observer (or other sensor) to even greater height (at first by aircraft, and later a space vehicle), and the use of radar, which works as well by night as by day, is able to penetrate fog and clouds, and to measure the distance to the objects being detected. Visual surveillance has been extended and improved in many ways, including sensitive camera film, detection in the infrared band, and use of electro-optical techniques (such as low-light-level television) to enhance sensitivity and to transmit images by wire or radio. Acoustic techniques have proven very successful for detecting the underwater noises of submarines, although much less useful with sound transmitted through the air.

While these new techniques have revolutionized the capabilities for surveillance, they each have their limitations, and a brief description of these limitations now follows.

Line of Sight

Visible light, and other forms of electro-magnetic energy useful for surveillance purposes, can be absorbed and scattered by clouds, rain, dust, or fog. But if the radiation escapes these diversions it is propagated through air or empty space in very nearly straight lines, at or very near the speed of light. An observer on a hill, a camera in an aircraft, or a television in a satellite has a "field of view", but this cannot extend beyond a horizon determined by the location of the sensor. The horizon as seen by an observer close to ground level is likely to be dominated by buildings, trees, or hills. But from higher altitudes the line of sight will extend as far as a horizon that is determined by the curvature of the earth, modified slightly by downward refraction of radiation when travelling nearly horizontally in the lower atmosphere.

For an aircraft 10,000 metres above the sea, the distance to the horizon will be beyond 350 km. From an altitude of 300 km above the sea, a satellite's horizon is nearly 2000 km away.[19] In practice, electromagnetic energy travelling nearly horizontally for long distances through the lower atmosphere suffers attenuation and scattering as well as refraction, so that useful observation of objects at zero or low altitude is unlikely when the rays graze the surface of the earth at angles of less than 3°. Figure 4 shows the cones useful for sensor operation, striking earth at grazing angles of 3°, as subtended by satellites orbiting at heights of 325, 807, and 1500 km. The powerful effect of altitude on a satellite's field of view is very evident.

The wavelengths used by infrared and radar devices are longer that those of visible light, and are subject to more complicated processes of absorption and scattering. However, for infrared as for visible light, it can be said that radiation which is not absorbed or scattered will be propagated in nearly straight lines, and is therefore cut off by the horizon. The same is true for the majority of radars and, as for visible light, returns will probably not be useful for grazing angles of less than 3°. However there is an important exception for high-powered radars using wavelengths in the HF (High Frequency) band. At these wavelengths certain layers of the ionosphere (located 50 to 400 kilometres above the earth) reflect radiation forward and downwards, allowing it to

---

[19] The horizon is determined by the curvature of the earth, and the curvature of the path of the radiation. However, it will usually be impossible to extend surveillance as far as the horizon from satellite altitudes.

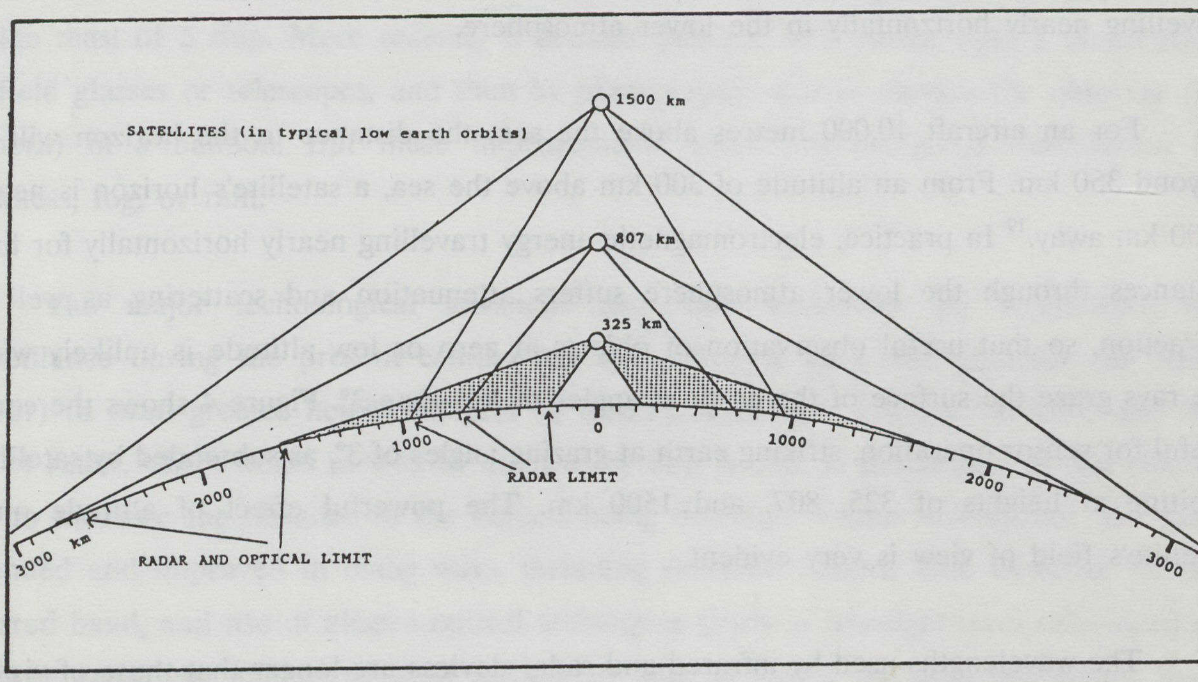

Figure 4
SWATH LIMITATIONS

reach targets beyond the horizon, and return back to the radar by the same reflected path. Thus the line of sight limitation does not apply to these specially designed "Over-the-Horizon" radars. This technique is of limited use in the Arctic regions due to the erratic behaviour of the ionosphere. A more detailed explanation of Over-The-Horizon radar can be found in Annex A.

The line-of-sight limitation is particularly severe for installations at ground level attempting to detect aircraft flying at low altitude. Unless the site is at the top of a dominating hill, a low flying aircraft will be below the radar's horizon unless the plane comes close to the site, and even then a fast moving aircraft will remain in view for only a very short time.

Resolution and Field of View

Optical design using long focal lengths allows the image recorded by a photographic or television camera to be magnified to any scale, although, for a given size of picture, greater magnification comes at the expense of displaying a smaller area of actual territory. As with a choice of maps of a given real size, one can show a large area on a small scale, or a smaller area magnified to a larger scale. However there are practical limits to the degree of magnification that is useful. Higher magnification spreads the received light over a larger area, and therefore reduces the brightness of the image, making it more difficult to recognize detail. Brightness can be increased by using a larger collecting lens, but large lenses are expensive, heavy,[20] and introduce optical aberrations of their own. The final limit to the ability to resolve the details of an image, posed by the phenomenon of

---

[20] For example, the Hubble Space Telescope launched on 24 April 1990, weighs approximately 1,200 kilograms (and costs about $2 billion). "Discovery Flies Unique Trajectory to Achieve Record Shuttle Altitude," *Aviation Week & Space Technology*, 30 April 1990, p. 23.

diffraction, inescapably associated with the propagation of waves, also depends on the size of the collecting lens.[21]

The most capable American and Soviet photographic reconnaissance satellites use large lenses and long focal lengths, accompanied by high resolution camera film or electro-optical systems capable of transmitting images to the ground without degrading the high resolution[22]. This represents a degree of high technology not yet matched by other countries, or by observation satellites designed for non-military purposes.[23]

The two factors determining resolution are the diameter of the collecting lens and the wavelength of the radiation. The larger the diameter of the lens and the shorter the wavelength, the better will be the resolution. Because infrared wavelengths are longer than those in the visual band, the images produced by infrared sensors cannot match the detail obtainable with visible light. In most other respects, infrared devices have the same

---

[21] Resolution, or resolving power, is a term describing the degree of detail that can be observed in an image. Once the detail becomes blurred, further magnification will not allow more to be learned from the image. The resolution can be limited by the grain size of photographic film, or by the number of pixel elements in a television screen, as well as by optical diffraction.

[22] George W. Stimson, *Introduction to Airborne Radar*, (El Segundo, California: Hughes Aircraft company, 1983) p. 516. As a general rule, the resolution required to recognize an object is somewhere between 5% and 20% of the major dimension of the object; for example, to recognize a house, a resolution of 2 - 3 metres would be required. Hugh De Santis, Commercial Observation Satellites and Their Military Implications: A Speculative Assessment, *The Washington Quarterly*, Summer 1989, p. 192. The author credits some United States systems with the ability to image objects as small as 10 centimetres. Vincent Kiernan, "Book Reveals Bickering Behind Scenes in Spy Satellite Programs," *Space News*, Volume 1, Number 1, 15 - 21 January 1990, p. 16. This author quotes a resolution capability for the American Keyhole or KH 11 photo reconnaissance satellite of six inches (15 centimetres).

[23] Bhupendra Jasani, "Space and Verification of Conventional Arms Reductions," *Brassey's Defence Yearbook,* 1989, p. 250. The best resolution from civil satellites so far is 10 metres, from the French SPOT spacecraft. The American high-resolution KH11 optical reconnaissance satellites are very large, weighing of the order of 14,000 kg.

limitations as those using visible wavelengths, such as the inescapable trade-off between magnification and field of view.

When we come to radar, the wavelengths exceed those of visible light by factors of hundreds of thousands, and the lens is replaced by the antenna. However the basic principles of resolution and field of view still apply. Because radar sends out its own pulses of energy, which are reflected from its targets, instead of simply receiving energy scattered from solar radiation, it is able to measure distance as well as determine direction, and by using very short pulses or clever coding of long pulses, can achieve good resolution in range. However, because it is not practical to construct antennas hundreds of thousands of times as large as optical lenses, the angular resolution achieved by conventional radar is much inferior to what can be accomplished by optical surveillance. In addition, since the angular beamwidth spreads with increasing distance from the antenna, the resolution degrades with range. In order to make the resolution in direction comparable to what can be achieved in range (say 10 metres)[24] the antenna on an aircraft would have to be about one kilometre long for observation of targets 100 km to one side of the aircraft. For a surveillance satellite the length of the antenna would have to be 4 km. Fortunately, modern techniques of storing and processing data are now enabling the signals received by a moving antenna of easily achievable dimensions to be collected and combined over a period of several seconds, in order to synthesize an image corresponding to what could have been produced by a stationary antenna that was as long as the distance moved by the smaller one during the several second period. This very important technique, known as Synthetic Aperture Radar (SAR), can be applied to aircraft or satellites, but requires advanced signal processing equipment. A brief description of the principles governing synthetic aperture radar is given in Annex B.[25]

---

[24] This would require a pulse length of 0.067 millionths of a second.

[25] S.A. Hovanessian, *Introduction to Synthetic Array and Imaging Radars*, Dedham, MA: Artech House, 1980. This book provides a good introduction to synthetic aperture radar, as does *Introduction to Airborne Radar*, op. cit.

Airborne or spaceborne radar is admirably suited for the production of high-resolution images of large stationary features on the ground. But if the purpose is to detect small objects on or close to the ground, then the principal problem facing a radar is the large amount of energy reflected back to it from the sea, from the ground, or from ice, snow or vegetation covering the ground. Unless special steps are taken to process the signals, the "clutter" will obscure the much smaller echoes from the targets of interest. Most of the transmitted energy that strikes a horizontal surface at a glancing angle is reflected outwards and upwards, with little returning back in the direction of the radar. Consequently, while clutter is usually so severe as to mask all targets directly or nearly below the radar, it will be less serious in directions far from the vertical. Figure 4 shows two cones beneath satellites at three altitudes, representing a glancing angle of 3° and 50° with respect to the horizontal at the point of reflection. Clutter normally renders radar detection impossible in the central "nadir" hole inside the inner cone beneath the satellite.[26]

This constraint on detection directly beneath the elevated radar does not apply to visual or infrared surveillance. However, the limitation represented by the outer cone, due to scattering and absorption of electromagnetic radiation in the lower atmosphere, is experienced by radar as well as by electro-optical sensors.

Detection of Colour, Heat, and Movement

An object under surveillance can be detected and identified only if it is in some way distinguishable from the background in its immediate vicinity. To the eye, it may look different because of its shape or colour, perhaps drawing attention because of movement. Colour is determined by the wavelengths of visible light reflected from the objects. The shortest (violet) and the longest (red) of the visible wavelengths differ by a factor less than two.

---

[26] G.N. Toandoulas, "Space-Based Radar," *Science*, Volume 237, 17 July 1987, p. 258.

All objects radiate energy as a result of their heat. If they are very hot, some of the radiation may be visible to the human eye, as in the case of the sun, a red-hot coal, or an electric light bulb. But for most objects at ordinary temperatures the radiation is in the infrared band, invisible to the eye but detectable by an infrared sensor. The wavelength of the radiation (its "colour") depends on the temperature, so that an object slightly warmer than its immediate surroundings will be distinguishable. This makes infrared surveillance particularly useful for the detection of rockets, ships, aircraft, and land vehicles, whose engine exhausts are much hotter than the immediate surroundings, and gives it special potential for use in the Arctic winter.

The band of wavelengths usually employed by various airborne or spaceborne radars is proportionately wider than the visual band, but narrower than the infrared band. However, it is technically difficult to make any one powerful radar operate at widely different wavelengths,[27] and the normal use in surveillance corresponds to illumination of the target area with radiation of a single "colour".

Human (and animal) vision is very sensitive to any rapid movement in a scene under observation. This advantage is lost in a still photograph (whether taken by visible or IR light), examined some time after exposure. A succession of still photos taken at intervals can be compared for any differences. This is a tedious business to carry out visually, but there are electronic means of identifying differences. Such delayed methods are more useful for detecting changes over periods of days or weeks, rather than for observing objects in motion.

With radar, it is possible to detect motion during the moment of observation. The precise frequency and phase of the energy transmitted by the radar is known, and can be stored for subsequent reference. If the radar itself is stationary, energy reflected from

---

[27] The physical size of many of the components associated with a radar must be matched to the size of the wavelength to avoid prohibitive losses when handling the energy. A component designed for one wavelength will not function effectively with another that is much different.

stationary targets will return with exactly the same frequency. But if the distance between the radar and the reflecting object is changing, the frequency of the reflected signal received by the radar (whether due to movement of the radar or of its target) will be slightly changed, and the amount of the change can be used to measure the rate of change of the range to the target.

Modern methods of storage and processing make it possible to use this (Doppler) effect to distinguish moving objects from stationary ones,[28] and of course the background which usually makes it difficult to detect wanted targets is normally stationary. Even if some of the unwanted background echoes are coming from moving reflectors (such as ocean waves when it is desired to detect ships, or the movement of automobiles when it is desired to detect aircraft in flight over the land), and if the radar itself is moving, it is possible to reject echoes from reflectors moving at less than some selected speed, chosen to be lower than the speeds expected for the desired targets. A brief summary of the principles employed by pulse doppler radar is given in Annex C.

---

[28] *Introduction to Airborne Radar*, op. cit., provides an excellent explanation of the basic doppler principle as well as a complete description of the application to airborne radars.

The Capabilities and Limitations of Orbiting Satellites

Ballistic Trajectories

In order to propel an object to a great distance it is necessary to overcome the forces of gravity and of air resistance. This can be achieved by continuous exertion of thrust throughout the flight, as is done by the engines of an aircraft, or by sudden acceleration to high velocity, followed by un-powered coasting in a ballistic trajectory, as is done with a shell fired from a gun. A disadvantage of a gun is that both it and its projectile must be very strongly built in order to withstand the forces needed to accelerate the projectile to high velocity in a very short period of time (no more than a few thousandths of a second). Intermediate between these extremes is rocket propulsion, by which the projectile is accelerated comparatively gently over a period of seconds or even a few minutes, thus reaching high velocity without having to withstand great stress.

A disadvantage of very long range rockets is that the original vehicle must include a large rocket motor containing plenty of fuel, attached to the payload that is to be sent to a great distance. Much of the fuel will be consumed in accelerating unburnt fuel and the motor. However, rocket propulsion permits very high velocities to be attained, especially when multiple motors are employed in successive stages, so that the first (and largest) stages can be separated after they have burned up their own fuel, leaving the later stages to propel only the ever-lighter remaining portions (including the payload). Burn-out velocities above three kilometres per second are sufficient to propel a rocket to altitudes at which air resistance becomes negligible, and beyond this the force of gravity itself becomes somewhat reduced.

In the case of an intercontinental ballistic missile, for which burnout velocity needs to be about 6.4 km per second, the elliptical trajectory curves downward only a little faster than the surface of the earth underneath it, so that it continues far beyond the horizon of the launching site before it falls back to the earth. See the trajectory labelled with burn out velocity 6.4 km per second in the upper diagram of Figure 5.

Given a velocity of more than 8 km/sec, the ballistic trajectory will become part of an ellipse whose complete loop would be large enough to encompass the earth. The upper diagram on Figure 5 shows two elliptical trajectories for burnout velocities of 8.0 and 9.3 km/sec., and also an escape trajectory with a burnout velocity of 11.2 km/sec., which never returns to earth. If the burnout velocity is sufficiently great, and is aimed in a nearly horizontal direction at a point well above the atmosphere, as indicated by point B in the lower diagram of Figure 5, then the projectile will continue to orbit around the earth in an elliptical path without any further propulsion, and we can describe it as a satellite. The inner orbit on the lower diagram is circular, and maintains a constant velocity of 7.7 km/sec. The outer orbit has a higher burnout velocity (8.0 km/sec at point B), but will slow down while moving through the higher portion of its elliptical path.

The time taken to complete one orbit, known as the period, depends on the velocity at the point of burn out (B) and the altitude of that point. After propulsion has ceased, the force of gravity will slow the satellite if it rises above the altitude of B, and speed it up if it drops below that altitude. The velocity needed to maintain a constant altitude is slower for high than for low (circular) orbits, so that the period increases for higher orbits. Two low circular orbits to be examined in this paper have altitudes of 325 and 807 km, the periods for which are 91 and 101 minutes respectively.

At altitudes below 200 km the upper layers of the atmosphere will exert drag on the fast moving satellite, and unless some compensating velocity is added the satellite will descend into denser air and soon be burned up as a result of the heat build up caused by friction. A circular orbit at an altitude of 200 km would have a period of 88.7 minutes.

At an altitude of 35,900 km a circular orbit has a period of 24 hours. If it orbits in the plane of the equator, the satellite will remain above the same point on the earth's surface. Such a "geo-stationary" orbit is too high for useful radar surveillance, although not too high for detection of the heat from the booster rockets of large missiles, or for the relay of communications.

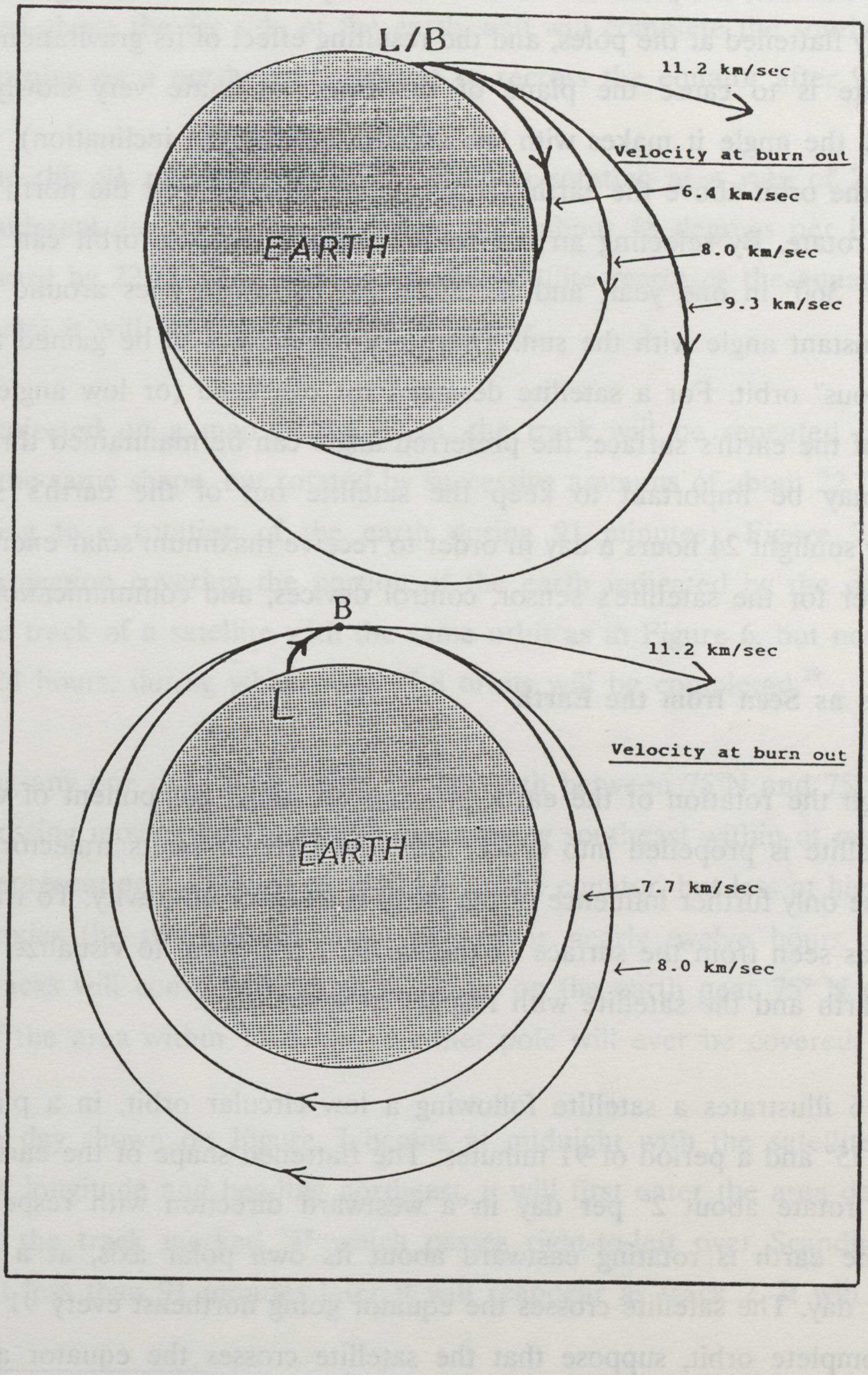

Figure 5

ORBITAL AND ESCAPE VELOCITIES

If the earth were a perfectly homogenous sphere, and if no further propulsion were applied to the satellite, the plane in which its orbit lay would never change. However, the earth is slightly flattened at the poles, and the resulting effect of its gravitational attraction on the satellite is to cause the plane of the orbit to rotate very slowly at a rate determined by the angle it makes with the equator (called the inclination), and also by the height of the orbit above the earth. Orbits passing directly over the north (and south) pole will not rotate. By selecting an inclination of about 98° the orbit can be made to rotate through 360° in one year, and therefore (as the earth goes around the sun) to preserve a constant angle with the sun. There are advantages to be gained from such a "sun synchronous" orbit. For a satellite designed for overhead (or low angle shadowed) photography of the earth's surface, the preferred angle can be maintained throughout the year. Or it may be important to keep the satellite out of the earth's shadow and illuminated by sunlight 24 hours a day in order to receive maximum solar energy to supply electrical power for the satellite's sensor, control devices, and communications.

Satellite Paths as Seen from the Earth

Although the rotation of the earth provides an initial component of velocity with which the satellite is propelled into space, once the latter is in its trajectory above the atmosphere the only further influence of the earth is its force of gravity. To trace the path of a satellite as seen from the surface of the earth, it is helpful to visualize the motions of both the earth and the satellite with respect to space itself.

Figure 6 illustrates a satellite following a low circular orbit, in a plane with an inclination of 75° and a period of 91 minutes. The flattened shape of the earth will cause this plane to rotate about 2° per day in a westward direction with respect to space. Meanwhile, the earth is rotating eastward about its own polar axis, at a rate of one revolution per day. The satellite crosses the equator going northeast every 91 minutes. To follow one complete orbit, suppose that the satellite crosses the equator at time 0 at longitude 0°, going northeastward. The point on the surface of the earth directly beneath the satellite will proceed on a track curving northeast towards east, graze latitude 75°N, and then moving to the southeast and behind the other side of the earth as seen on Figure 6. After 45.5 minutes the satellite will recross the equator, now moving southeastward above the far side of the earth, and will complete the southern half of its orbit by returning on a northeasterly course to recross the equator after 91 minutes.

During this 91 minutes, the earth, which is rotating at a rate of 360° every day (actually a sidereal day of 23 hrs, 56 min, 4 sec), about 15 degrees per hour, will have turned eastward by 22.75°. Therefore when the satellite recrosses the equator at the end of its first orbit it will be at 22.75° West longitude.

As projected on a map of the earth, the track will be repeated on subsequent orbits, with the same shape, but rotated by successive amounts of about 22.75° to the west (corresponding to a rotation of the earth during 91 minutes). Figure 7 shows, on a gnomonic projection covering the portion of the earth indicated by the dotted lines on Figure 6, the track of a satellite with the same orbit as in Figure 6, but now covering an interval of 24 hours, during which time 15.8 orbits will be completed.[29]

During any one day, every point on the earth between 75°N and 75°S latitude will have one crossing moving northeast and one moving southeast within at most 11.4° of its longitude (representing a distance of 1270 km at the equator, but less at higher latitudes). At low latitudes the two closest passes will occur nearly twelve hours apart. Several successive tracks will come quite close to points on the earth near 75° N (and 75° S). But none of the area within 1600 km of either pole will ever be covered.

If the day shown on Figure 7 begins at midnight with the satellite crossing the equator at 0° longitude and heading northeast, it will first enter the area depicted on the figure along the track marked "1" which passes right-to-left over Scandinavia and the USSR. A bit less than 91 minutes later it will reappear as track 2. It will not cross

---

[29] These paths include the 2° per day correction for the rotation of the orbital plane because of the non-spherical shape of the earth.

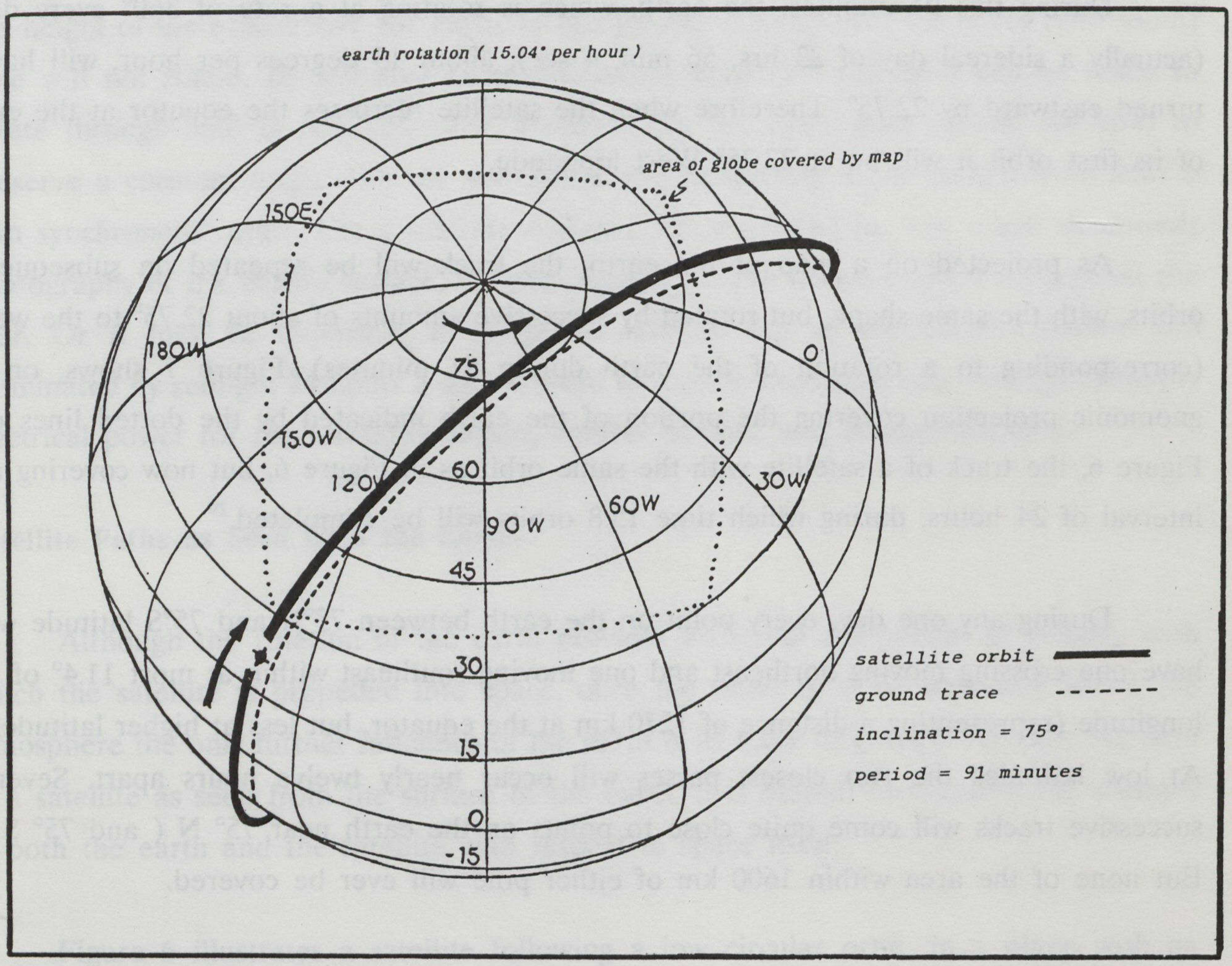

Figure 6

LOW-ALTITUDE SATELLITE ORBIT AROUND THE ROTATING EARTH

Canadian territory until more than 4½ hours have elapsed, when track 4 crosses Newfoundland heading northeast. Following this, at approximately 91 minute intervals, each of track 5 to track 13 cross part of Canada. During the 24 hours, ten of the 15.8 orbits cross some part of Canada.

On Figure 7 the ground track under the seventh orbit is drawn with a swath width of 100 km, centred under the orbital path. The seventh orbit crosses the equator 9 hours and 6 minutes after the beginning of the day being illustrated. The hatch marks show where the satellite is at two-minute intervals between 9 hours 16 minutes and 9 hours 36 minutes. Moving at 460 km/minute the satellite is above Canadian territory for eight minutes (between 9 hours 19 minutes and 9 hours 27 minutes).[30]

From Figure 6, it is clear that it will take a single satellite several days before its ground track can pass within 50 km of every point inside or near Canadian territory.

The territory of Canada is all between latitudes 42°N and 82°N. Therefore a satellite for surveillance of the Canadian North or the Arctic Ocean would have to be in an orbit with an inclination close to 90°. This has the property of overflying all of the earth's surface, whether or not territory south of 42°N is of interest.

One way to keep a satellite over northern latitudes as much as possible is to employ a highly eccentric (elongated) elliptical orbit, which comes close to the earth when it is at its southern extremity, and moves very fast, but departs to very high altitude over the northern hemisphere, above which it moves more slowly and therefore spends more time. Such an orbit can be given a period of 12 hours, so that its long dwell time above

---

[30] The slight curvature of the tracks on Figure 7 is due to the rotation of the earth. If the earth did not rotate, the tracks would be straight lines on the gnomonic projection. But in the 20 minutes it takes to cross the mapped area the earth rotates through 5°, just enough to produce a noticeable curvature.

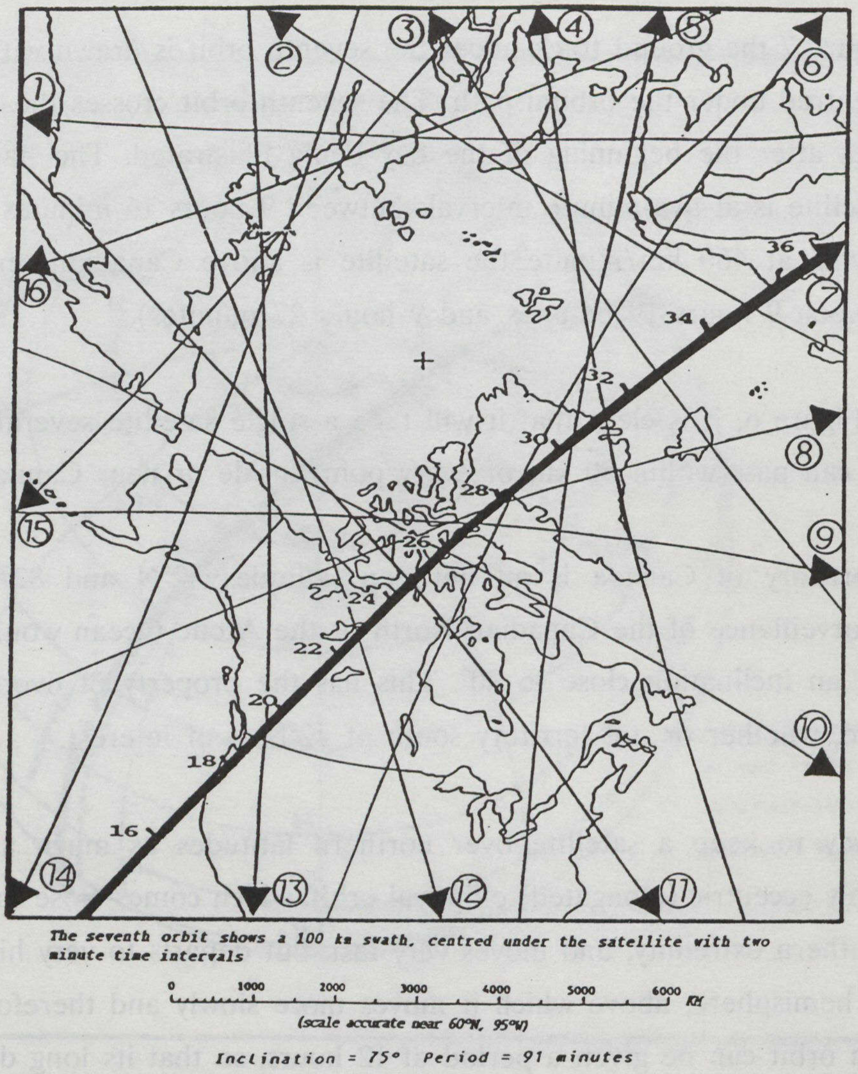

Figure 7
TWENTY-FOUR HOUR COVERAGE

the northern hemisphere occurs twice a day. However, the altitude there will be very high (10,000 to 35,000 km) which, while acceptable for communication satellites, is probably too far above the earth for most roles of surveillance.

The Limited Manoeuvring Capability of a Satellite

It takes a very large rocket on the launching pad to send a comparatively small payload into orbit. A typical case would have 90% of the total weight in the form of rocket fuel, with the eventual payload that goes into low-earth orbit weighing only about 2 or 3% of the original all-up launch weight. This is the fundamental reason why it has not been possible to bring the cost of putting a kilogram of payload into orbit below several thousands of dollars.[31]

If the satellite is to have any residual capability to manoeuvre into a different orbit, some of its very limited weight will have to include a rocket motor and unburnt fuel, leaving correspondingly less weight for whatever primary function the satellite has been sent up to perform. If it is desired to have the satellite pass above some particular place on the earth, and some delay can be accepted, by far the easiest course is to leave the satellite to follow its elliptical trajectory in space, and to wait for the combination of its and the earth's motion to bring them into the wanted relative positions. It is possible to slew certain sensors on board a spacecraft to examine a specific area; however, that area must be within the satellite's field of view.[32]

---

[31] "Launching into Low Earth Orbit should be Economical and Routine", *Aviation Week & Space Technology*, 27 November 1989, p. 93. This article places launch costs on the Space Shuttle at $6,000 - $10,000 per pound ($13,200 - $22,000 per kilogram) and about half that using expendable launch vehicles. Thus the approximate cost of launching a satellite like RADARSAT (weighing around 4,000 kg), using an expendable vehicle, would be in the region of $40 million. Building the satellite would likely cost very roughly ten times this sum.

[32] The Canadian remote sensing satellite, RADARSAT, will have its sensor slewed to the right during its lifetime except for two occasions when it will be slewed to the left in order to see Antarctica.

Notwithstanding these limitations, if a heavier launching vehicle is available, it is possible to include a limited capability for manoeuvring propulsion in the orbiting satellite. The dynamics of low-earth orbits are such that a slight increase in the minimum height (as may be necessary to stay above the drag of the atmosphere) does not require very much additional energy. However, changing the plane of the elliptical orbit (as would be necessary to alter the locations on the earth over which the satellite tracks pass) is very expensive in fuel.

Summary

The outstanding characteristics which need to be kept in mind when considering the use of satellites for surveillance of territory in the latitudes in the vicinity of Canada are:

(i) The most northerly latitude on the surface of the earth that can be surveyed is determined by the inclination of the plane of the orbit;

(ii) Although possible, it is extremely costly to provide the capability for a satellite to alter the plane of its orbit; and

(iii) For low altitude orbits (likely to be the most attractive for surveillance), the track of the satellite will pass within at least 900 km (and often much less) of all points on the surface of the earth with latitudes north of 45°N but lower than the inclination of the satellite's orbit, twice every day, at intervals of about twelve hours. For points with latitudes close to the angle of inclination there will be several crossings closer than this every 24 hours.

Coverage of Canadian Territory by a Single Satellite

Figure 7 showed the ground tracks of a single satellite in a low circular orbit with a period of 91 minutes and an inclination of 75°, as it passed across the part of the earth in the vicinity of Canada, during an interval of 24 hours. Examination of the diagram shows that the degree of coverage varies with the latitude, being sparse to the south of the Canadian/US border (along latitude 49°N west of Ontario), increasing gradually and then more rapidly to a maximum around 75°N (at which latitude the track reaches its greatest excursion to the north), and quickly dropping to zero north of 75°N. This situation is shown in graphical form on Figure 8, which plots the average number of times in 24 hours that a swath crosses any point at a specified latitude. The lowest curve on Figure 8 indicates that 100 km. swaths cover latitudes south of 66.6°N (the Arctic Circle) less than 0.25 times a day, in other words with an average accessibility interval longer than four days. But in the vicinity of 75°N they average more than one crossing per day (accessibility interval less than 24 hours). The accessibility interval is indicated up the right hand margin of Figure 8.[33]

Obviously the coverage will improve for greater swath widths. Figure 8 shows the coverage for swaths measuring 200, 300, 500, and 1000 km across, each centred on the ground track directly underneath the 75°, 91 minute satellite orbit. The 1000 km swath would have an accessibility interval less than 24 hours over all of Canada, and less than 12 hours for latitudes between 63°N and 78°N.

Figure 8 can be used to estimate the number of satellites that would be required to produce a given accessibility interval at a given latitude. For example, every point on the Arctic Circle would be crossed 2.5 times a day by 1000 km swaths, and 1.25, 0.75, 0.50, and 0.25 times a day by swaths of widths of 500, 300, 200, and 100 km respectively. Therefore, an average accessibility interval of 12 hours or less, achievable with a single satellite capable of surveying a swath of 1000 km, would require two satellites with a swath of 500 km, three with 300 km, four with 200 km, or eight with 100 km.

---

[33] The curves of latitude coverage in Figures 8 and 9 are calculated from the geometrical intersections of the left and right edges of the swath with each parallel of latitude. A small correction is necessary for the rotation of the earth, which reduces the coverage slightly for orbits with inclinations less than 90°.

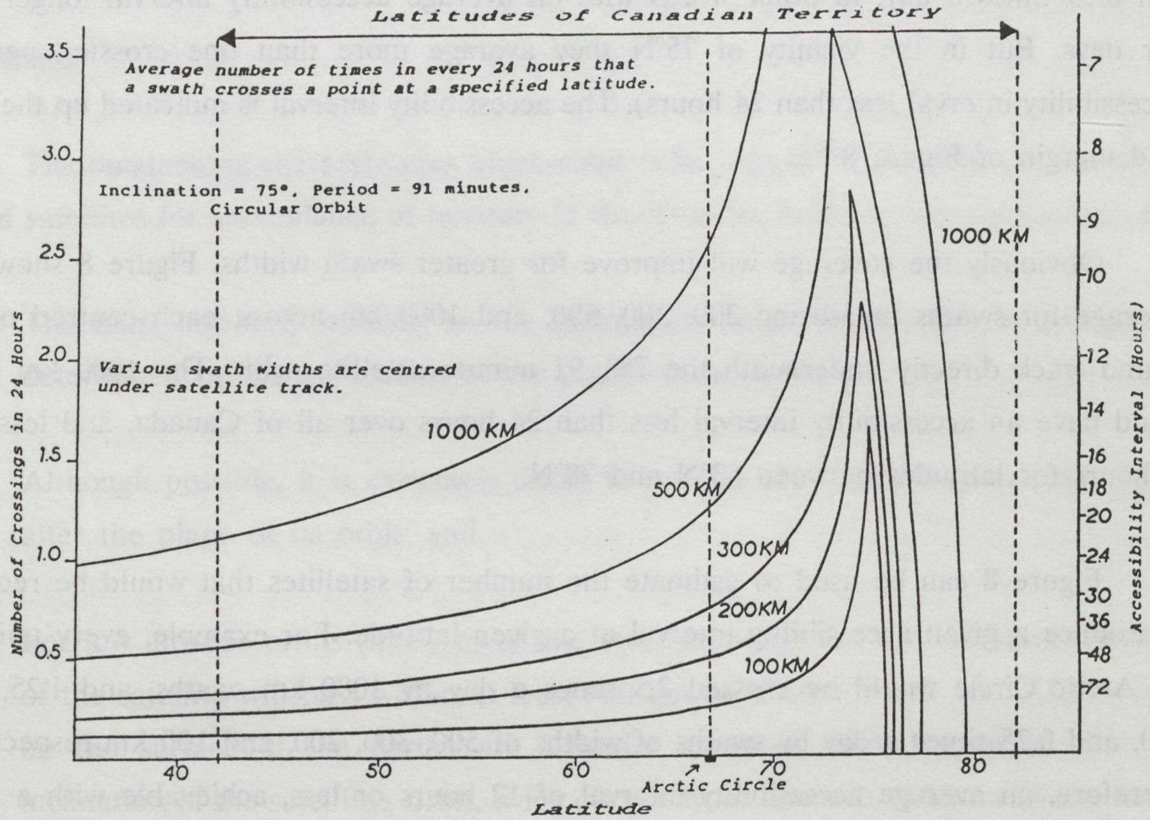

Figure 8

LATITUDE COVERAGE
(75° Inclination: Various Swaths)

Figures 7 and 8 showed orbits with inclination 75° and period 91 minutes. Figure 9 depicts comparable information for inclinations 60°, 70°, 75°, 80°, and 90°, each still with a 91 minute period and a swath width of 100 km centred on the ground track. Reducing the inclination makes a very small improvement to the coverage at lower latitudes, but more for latitudes just below the inclination angle. It removes all coverage much beyond the inclination angle. The absolute maximum (above the limits of Figure 8) is the circle of radius 50 km from the north pole, which will be crossed 15.8 times (i.e. by every orbit) by the 100 km swath of a satellite with an inclination of 90°, giving an accessibility interval of 91 minutes. If the period is increased, the number of daily crossings will be proportionately reduced.

RADARSAT, a satellite planned for remote sensing over Canada, is to have an inclination of 98.5°[34] and a period of 101[35] minutes. This was chosen to produce a circular sun-synchronous orbit. RADARSAT's synthetic aperture radar is designed to survey a swath beginning 250 km to the right of the ground track (beyond the nadir hole) and ending 750 km to the right. The coverage of this satellite is shown on Figure 9 as a dashed line, with the number of crossings in 24 hours for latitudes between 83°N and 88°N being too large to be plotted on the diagram. These 500 km offset swaths are also shown on Figure 10 for the 14.3 orbits completed in 24 hours. The swath of a single RADARSAT will survey every point above latitude 69°N at least once a day (on the average), but the more southerly areas of Canadian territory will have accessibility intervals of about two days.

---

[34] An orbit with an inclination between 90° and 180° is said to be "retrograde" as it is moving westward.

[35] "Team of Canadian, U.S. firms begins detailed design work on Radarsat", *Aviation Week & Space Technology*, 12 February 1990, pp. 111-115.

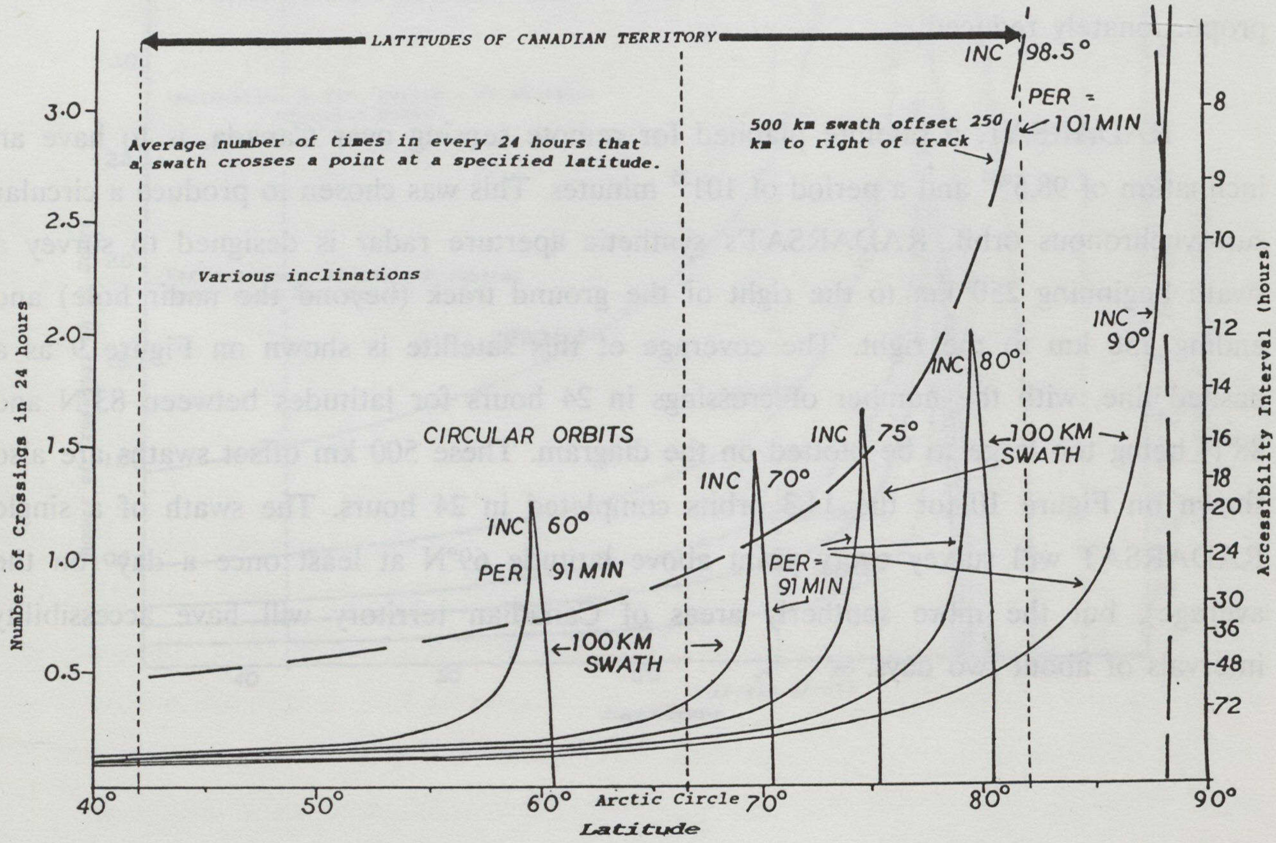

Figure 9

LATITUDE COVERAGE

(Various Inclinations)

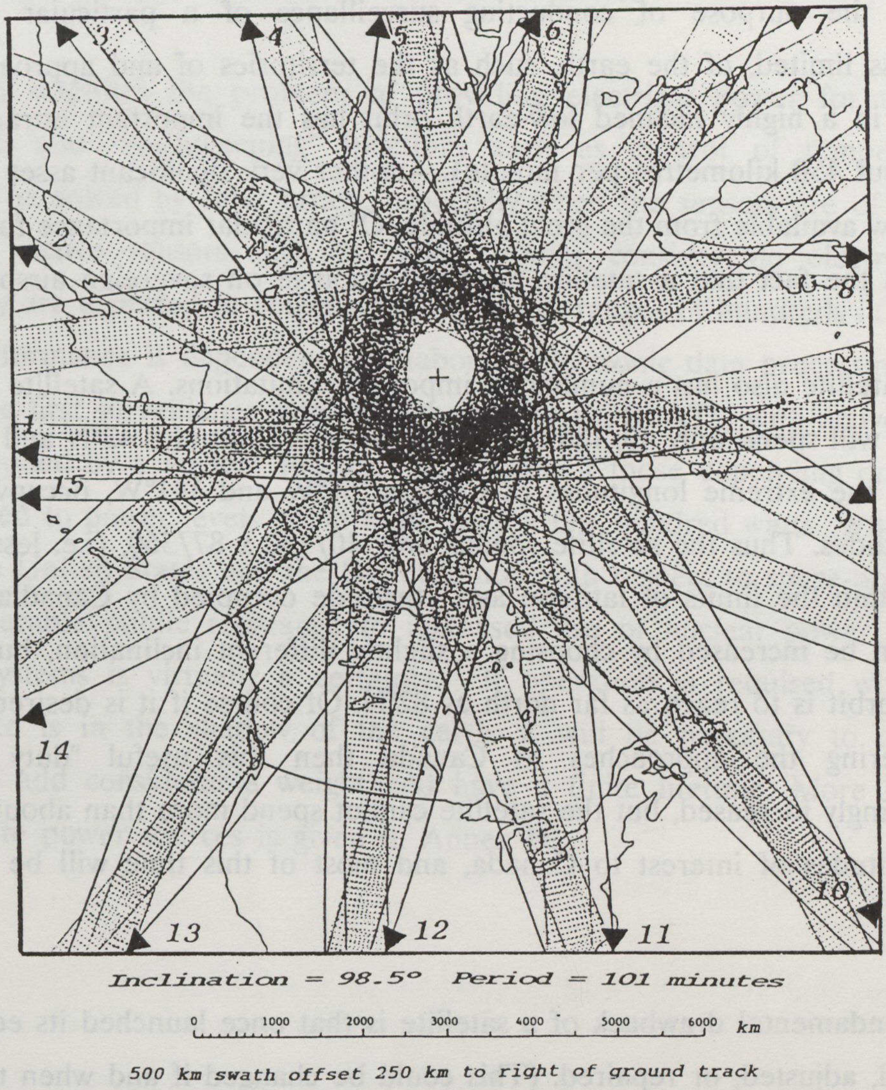

Figure 10
TWENTY-FOUR HOUR COVERAGE

Comparison of Spaceborne, Airborne and Ground-based Surveillance

The Strengths and Weaknesses of Satellite Surveillance

For the purpose of conducting surveillance of a particular area, large but nevertheless limited, of the earth, such as the territories of and approaches to Canada, a satellite in a highly inclined low-earth orbit has the important attraction of its high speed (about 450 kilometres per minute). Another very significant asset is the enormous field of view available from the great altitude. Of particular importance for reconnaissance activities is the fact that a satellite does not impinge on sovereign airspace.

A satellite also has a number of important limitations. A satellite in a 90° circular polar orbit will spend only 40/180 of its time between latitudes 42°N and 82°N, i.e., about 22 %, and the extreme longitudes of Canada, 54°W and 141°W, occupy only 87/360 of all the latitudes. Thus the satellite spends only 40/180 x 87/360, (i.e. less than 5.4 %) of its time within the limits of latitude and longitude occupied by Canadian territory. This fraction can be increased by choosing a slightly different inclination, but will not attain 7% if the orbit is to reach as far north as 82°N. Of course if it is desired to survey large areas covering the approaches to Canada then this useful "duty cycle" will be correspondingly increased, but the satellite cannot spend more than about a quarter of its time at latitudes of interest to Canada, and most of this time will be at uninteresting longitudes.

A fundamental drawback of a satellite is that once launched its equipment cannot be replaced, adjusted, or repaired. (This could be changed if and when the space shuttle becomes fully operational, but the cost is likely to be very high).

Other serious problems for surveillance satellites are the lack of manoeuvrability, the distance from the surface of the earth, the difficulty of providing large amounts of electrical power, and the presence of the atmosphere. There will be no more than two opportunities every 24 hours to observe any one small area of special interest, and often only one or none at all. If the sensors cannot operate through cloud, fog, rain or in the dark, the surveillance is prevented. To minimize atmospheric drag, the satellite must keep at least 150 km above the earth's surface, so that the range to objects under surveillance will never be less than this considerable minimum distance.

For most satellites the problem of providing electrical power for the sensors, communications, and "housekeeping" functions such as control of temperature and orientation can be solved by solar arrays, especially when the sensors are of the passive type. However, active sensors such as radar require considerable electrical power, especially if they are expected to detect small objects at ranges of hundreds of kilometres, and if their performance is dependent on elaborate electronic data processing on board the satellite. The first surveillance satellites (the Soviet RORSATs) with active radar had their power supplied by a nuclear reactor,[36] and most of those depending on solar cells have been limited to power levels of no more than a few hundred watts. While research continues in the United States and the Soviet Union with respect to space-borne nuclear reactors, considerable public resistance to increased use of nuclear power sources for earth-orbiting systems is virtually a certainty.[37] If operation is required while a solar powered satellite is in the shadow of the earth, it will be necessary to add storage batteries, which add considerable weight and have a finite lifetime. More information regarding satellite power sources is given in Annex D.

---

[36] Daniel Hirsch, "Soviet Reactors for SDI?", *International Affairs*, January 1990: p. 154. The "Ramashka" reactor was the type on board COSMOS 954 that crashed over northern Canada in 1978.

[37] "Anti-Nuclear Groups Oppose Galileo Launch, Jupiter Probe Powered by Plutonium," *The Washington Post*, 16 September 1989: p. A3.

The Strengths and Weaknesses of Airborne Surveillance

As platforms for surveillance of activity on the surface of the earth, manned aircraft have had remarkable success, at first with visual observation, then photography, and more recently with radar, electro-optical, and other modern sensor systems.

Aircraft cannot match satellites in speed of sweeping over the earth. Instead of 450 kilometres a minute they may cover 15. Neither do they have as large a field of view, although this is often unimportant because the useful maximum range is limited by factors other than line of sight. In peacetime they must also obey the stricture of not violating sovereign airspace of another country without permission.

Aircraft far excel satellites in manoeuvrability, ability to fly under cloud and close to targets, and ease with which electrical power can be supplied. A large aircraft can be quickly dispatched to examine an area of interest and remain there for hours. Moreover, in the case of targets wishing to avoid observation, the arrival of the satellite is predictable, while the aircraft is more likely to appear without warning.

A major advantage of manned aircraft is the opportunity to change or repair sensors between missions, or (often) to adjust them in flight. Another is the capability of the crew to observe something unexpected, but of potential interest, and quickly modify the mission in order to investigate further.

The Strengths and Weaknesses of Ground-Based Surveillance

The greatest limitation of ground-based surveillance is the line of sight. The area of the earth's surface or the volume of air that can be observed from a point no more than a few feet above ground level is extremely small when compared to the field of view from a satellite or a high-flying aircraft. An exception can occur at a particularly advantageous site such as on a high mountain overlooking a flat plain or the sea.

The strength of ground-based surveillance is its continuous presence, able to ensure close to full-time coverage throughout the year. The size of antennae, volume of signal processing equipment, and supply of electrical power are not constrained by the limitations of a mobile vehicle. In remote northern locations attendance of operators and maintenance personnel is expensive, but this problem is being alleviated by minimum manning of installations and sending data to central operations centres, and by highly reliable electronics with automatic switchover to standby units in the event of component failure.

Against a planned attack, the vulnerability of surveillance installations would be a consideration, both for the threat of destruction and for electronic countermeasures designed to prevent both detection and recognition that hostile activity was in progress. Ground-based systems are the most vulnerable, aircraft less so, and satellites the least of the three.

Relative strengths and weaknesses of spaceborne, airborne, and ground-based surveillance are summarized in Table A.

Table A

COMPARISON OF SPACEBORNE, AIRBORNE, AND GROUND-BASED SURVEILLANCE

SATELLITE SURVEILLANCE

Strengths

- large swept area in a short period of time
- large field of view
- not limited by line of sight restrictions
- centralized ground infra-structure can be located in area of choice
- no territorial restrictions

Weaknesses

- coverage restricted to territory under orbit
- long re-visit time
- sensors have high initial cost, cannot be repaired on orbit and cannot be modified
- predictable flight path, difficult and expensive to alter once established
- difficult to generate high prime power on orbit without use of nuclear reactors
- complex command and control
- information must be remoted for decision making

AIRCRAFT SURVEILLANCE

Strengths

- can generate relatively high power levels
- equipment can be modified and maintained relatively easily
- mature technology, little risk in system performance
- components less costly than space qualified ones
- flexible and manoeuvrable, can fly below cloud cover
- line-of-sight restrictions far superior to those at ground based installations, good look-down low level target detection capability
- sensors display and decision making or information can be remoted

Weaknesses

- carriage of large antenna structures cumbersome
- requires basing and infra-structure close to operating areas for rapid response
- relatively short mission durations, requires a large number of resources for continuous coverage
- subject to territorial limitations
- manpower intensive

GROUND-BASED SURVEILLANCE

Strengths

- very high power levels possible
- very long ranges possible with direct path to elevated targets
- can utilize ionospheric bounce to increase ranges well beyond line-of-sight
- can utilize very large antenna structures, provides frequency flexibility
- system can be manned for real time display and decision making, or information can be remoted
- equipment can be modified and maintained
- components are less costly than for airborne or spaceborne applications

Weaknesses

- line-of-sight limitations reduces the ability to detect low targets (minimized by siting on high ground, which can cause logistic difficulty)
- inflexible geographically once installed
- most convenient to be at least semi-permanently located in the area to be covered
- manpower and infrastructure intensive
- vulnerable to attack

PART III - THE ROLE OF THE CANADIAN ARMED FORCES IN SURVEILLANCE

The Cyclic Character of the History of the Canadian Armed Forces

Since the beginning of this century the size of the Canadian Armed Forces has undergone a series of major fluctuations, the reasons for which have been dramatic changes in the world situation and a vacillating policy regarding the desirable magnitude of the Canadian contribution to defence.

Based on a tiny permanent force of about 3,000 and a healthy militia (about 60,000 strong), recruiting of volunteers for the Canadian Expeditionary Force in World War I raised a very large army. The technology of the day allowed armaments to be manufactured and soldiers trained within a period of a few months. Eventually, heavy casualties made conscription necessary, and by 1918 the number of Canadians who had enlisted had attained a peak of around 628,000, drawn from a total population of about 8,000,000.[38]

In 1919 this large force was demobilized, leaving a very small permanent force which fell to less than 4,000, and numbered about 5,200 in 1935, with air and sea as well as land elements, but a strong and enthusiastic reserve force over 49,000 strong.[39]

A similar cycle was repeated in 1939, when World War II began with Canada's permanent force numbering about 8,000, and the reserves about 54,000. Large numbers volunteered for air force and navy as well as army service. Manufacture of aircraft, warships, tanks, radar, sonar, and weapons required considerably more time than in the first war, as did the training necessary to make effective airmen, sailors, and soldiers. It took many months before Canada was able to make a sizeable contribution, but the war lasted nearly six years and over one million Canadians enlisted. Again, casualties obliged

---

[38] C.P. Stacey, *The Military Problems of Canada*, Toronto: Ryerson Press, 1940, pp. 76 - 77.

[39] C.P. Stacey, *Arms, Men, and Governments: The War Policies of Canada 1939 - 1945*, Ottawa: The Queen's Printer, 1970, pp. 1 - 5.

recourse to conscription, and at one time there were nearly 800,000 Canadians in the armed forces, out of a population of slightly over 11,000,000.

Demobilization in 1945 was less complete than in 1919, leaving about 35,000 in the regular army, air force, and navy by 1948, and strong reserve forces. Beginning in 1950, the needs of the Cold War exceeded the capabilities of the regular force, and volunteers were recruited for service in Korea. The regular force grew to a maximum of 125,000, including a large air element. Most types of the necessary modern armaments could be manufactured in Canada, but the forces did not possess heavy bombers, and eventually lost their one aircraft carrier and the nuclear weapons supplied by the United States. During the last twenty years the size of the regular force has decreased to about 85,000,[40] the number of combat aircraft and warships has been sharply reduced, and the reserves have declined.

Now that the Cold War is perceived to be ending, a further reduction in the resources devoted to defence is foreseen. The problem for the planners is to design this reduced force for the long-term requirements of the future.

Difficult in any department of the Canadian government today, realistic long-term planning faces special problems in National Defence. The immediate dangers in Europe appear to be sharply reduced. The future of NATO, the keystone of Canadian defence for forty years, is unclear. The urgent need to address the heavy and growing national debt puts special pressure on the budgets of departments whose programmes are primarily discretionary rather than statutory.

Assuming reductions in commitments and in manpower, the planners will need to accept a substantially decreased capability for immediate readiness. They should focus instead on the building and preservation of capabilities that may be required in the future, designing a force of modest proportions but with the capacity to expand in a period in which high technology is even more important than it is today.

---

[40] *Defence 88*. Ottawa: Minister of Supply and Services Canada, 1988.

Desirable Technology for the Canadian Armed Forces of the Future

Any worthwhile long-term plan for a defence organization able to exploit modern technology, let alone technology of the future, must take into account the long and growing delay that passes between recognition of the need for new equipment and the eventual effective employment of the finished product in operational service.

Research, development, testing, evaluation, decision to procure, production, and correction of faults can easily consume seven to ten years or more[41] for large programmemes, often extended further by administrative delays and reviews. Even with some preparation before the new equipment becomes available, training of operators cannot be complete until after a subsequent opportunity for familiarization. Training periods for very complicated weapon systems, such as the CF-18 fighter aircraft, can easily exceed one year.

Should rapid expansion of military capabilities become necessary, it may be possible to expedite production of additional units of equipment already on the line and to recruit new personnel to operate it. But the training of these recruits will depend on the availability of regular cadres already possessing the necessary experience.

It follows that the armed forces of the future should be equipped with some (perhaps not very much) of the most advanced equipment. The Department of National Defence should be sufficiently familiar with current technology to be able to identify the types of equipment likely to be needed in future years, and must equip the armed forces with selected systems on a scale sufficient to maintain enough expertise to conduct such limited operations as may be required in peacetime, and to serve as the nucleus of rapid expansion if this should be needed in future.

While selection of the roles and equipment must be based primarily on the requirements for security, every opportunity should be taken to enable the armed forces

---

[41] "Maine OTH-B completes ...," p. 52. This article points out that "OTH-B is transitioning to deployment 20 years after a program office was established ... and 15 years after General Electric Aerospace received a contract for a prototype system in 1975."

to perform tasks that make valuable contributions to the country in times of peace. In many instances the equipment and skills needed for defence are transferable to non-military functions, and rather than considering their exercise as an undesirable diversion from military training, it should be seen as a welcome opportunity to be useful in peacetime, while still maintaining a readiness, perhaps somewhat reduced, to meet unforeseen emergencies if and when they should arise.

It may be argued that civil functions are already adequately handled by other departments of government, or by the private sector. However, a country with a national financial deficit as large as Canada's needs to seek economies where possible, even if they should involve some redistribution of responsibilities among government departments. Moreover, newly emerging non-military threats such as environmental degradation[42] and international drug traffic,[43] as well as the need to verify arms control agreements, are likely to create requirements for monitoring of types not currently undertaken by any national organization. While a military organization may easily adapt to a civil function, an organization manned and trained to perform a civil function is unlikely to be able to fulfil a military security role in times of need.

Of the various functions conducted by DND which resemble in some degree functions necessary for non-military purposes, an important category comes under the heading of surveillance. Considering the opportunities now being offered by new technology, a study of the requirements for surveillance for the security of Canada should examine the potential of a suitably equipped defence organization to provide a parallel service to provide surveillance for national civil as well as defence needs.

---

[42] Michael Driedger and Don Munton, The 1989 CIIPS Public Opinion Survey, *Security, Arms Control and Defence: Public Attitudes in Canada*, Ottawa: The Canadian Institute for International Peace and Security, 1989. When asked to rank the three international threats (military, economic and environmental) facing Canada, now and ten years in the future, less than 7% of respondents felt that the military threat was the most serious. Environmental and economic threats were considered to be far more serious.

[43] "Congress Pressures Military to Assume Direct Antidrug Role," *Aviation Week & Space Technology*, 23 May 1988, pp 25 - 27.

PART IV - THE SUITABILITY OF VARIOUS SENSORS AND PLATFORMS FOR SURVEILLANCE OF CANADA

Relevant Canadian Surveillance Activities Presently Active or Planned

Canada is currently involved with two space-based surveillance activities of interest to this paper. The first is primarily a civilian activity under the leadership of Spar Aerospace called RADARSAT. The second is a cooperative venture between the Canadian Forces and the United States Air Force to develop a space-based wide area surveillance system to provide the follow-on capability needed to meet NORAD requirements.

The RADARSAT[44] programme consists of an earth observation satellite employing synthetic aperture radar, to be launched in 1994, with the United States National Aeronautics and Space Administration participating in the project by providing the launch on a Delta 2 rocket. The United States is also providing the use of a ground station in Alaska in return for US access to the data to be gathered by the system.

The Canadian government initially approved RADARSAT in 1987, on a cost sharing basis with the provinces (\$59.2 million from Quebec, Ontario, Saskatchewan and B.C.), with the federal government paying \$330 million towards the project. The team is led by Spar Aerospace of Toronto under contract to the Canadian Space Agency, and consists of a consortium of Canadian and American companies. This consortium, called Radarsat International, will market data worldwide.

The satellite sensor is a synthetic aperture radar with a swath to the right of the spacecraft. The terrain swath to be imaged can be 500 km wide with a resolution of 100 m, or as narrow as 45 km with a resolution of 10 m. The orbital altitude will be 792 km (with a period of 101 minutes) at an inclination of 98.5° in a sun-synchronous orbit. The swaths on Figure 10 and one of the coverage curves on Figure 9 were chosen to match

[44] "Team of Canadian, U.S. Firms Begins Detailed Work on Radarsat," *Aviation Week & Space Technology*, 12 February 1990, p. 111.

the parameters planned for RADARSAT. The satellite will be able to operate continuously for 15 min on each orbit and up to 28 min for limited periods of time.[45]

Data will be provided within 3 hours of overflight, and the system will provide daily coverage of the high Arctic, coverage of Canada every three days and global coverage every 24 days. The radar will use a 300 watt transmitter with power coming from a 2.5 kw solar array.

The Canadian government has also committed itself to a joint research programme with the United States for space-based air surveillance[46] and decided to cooperate with the United States on the Air Defence Initiative looking for ways to "develop technologies appropriate to surveillance, interception and battle management in regard to hostile bombers and cruise missiles."[47] This programme will investigate both infrared and radar technologies, although it appears at this point that radar is the favoured sensor. The primary infrared satellite experiment, called Teal Ruby, has been placed in storage.[48] The space-based radar programme will likely employ pulse doppler radar technology and a large constellation of satellites designed to provide worldwide coverage - a requirement clearly stated for the US Air Force and the US Navy. Although the wide area surveillance project is a joint venture with the US, a strictly Canadian research and development project for $50 million has been funded to investigate these technologies.[49]

---

[45] This limit is imposed because of heat dissipation requirements.

[46] *Challenge and Commitment*, pp. 56 - 59.

[47] Joel Sokolsky, *Defending Canada, US - Canadian Defense Policies*, New York: Priority Press Publications, 1989, p. 31.

[48] "Teal Ruby Spacecraft to be put in Storage at Norton AFB," *Aviation Week & Space Technology*, 8 January 1990, p. 22.

[49] "Canada Regards Space-Based Radar As Follow-On to North Warning System," *Aviation Week & Space Technology*, 28 September 1987, pp. 136 - 137. This article states that the $47 million research and development program under the auspices of the Department of National Defence is intended to expand Canada's industrial base in space-based radar technologies and facilitate future collaboration with the U.S. Department of Defense.

Remote sensing from aircraft is well developed in Canada and is being used for many civilian purposes,[50] including the passive radiometric study of ice in the Arctic to differentiate between old and new ice.

The Capabilities of the Various Sensors and Platforms to Meet the Requirements of the Different Types of Surveillance

In assessing the suitability for the requirements of Canadian surveillance of the various sensors and platforms, it is necessary to identify certain major characteristics of the objects of the surveillance. The most important of these are the extent to which they are detectable, and identifiable, whether they are moving, and the time delay that can be accepted before the information is delivered to the appropriate authority.

Target size, expressed in square metres, is a measure of detectability to both optical and radar sensors, although there are of course other factors such as colour, material, and shape, and very much depends on the background against which the target must be distinguished. Target velocity is significant for two reasons. Motion with respect to its background may make it detectable, as is the case with Doppler radar. Also, if it is in motion it may be necessary to track its progress, in which case the permissible interval between successive observations cannot be long, and it may not be acceptable to have a long delay before the detection and subsequent track is reported. The extreme cases are ballistic missile warheads moving at 7 km per second and due to impact within a few minutes, as contrasted to mapping imagery that will hardly change from year to year. Apprehension of a boat approaching the coast might allow a delay of an hour or two.

Electro-optical sensors are divided into visual and thermal, the former depending on size, shape, and colour contrast with the surroundings, and the latter on temperature difference from that of the surroundings. For example, the exhaust form a large passenger jet aircraft will radiate far more heat than will be produced by a cruise missile. An

---

[50] For example, a synthetic aperture radar developed by MacDonald Detwiller in Vancouver has been in use since 1983 and has applications in areas of forestry, agriculture, hydrology, ice surveillance, disaster assessment, geology and mapping.

infrared detector capable of distinguishing a temperature difference of 1°C would detect the aircraft but not the cruise missile.

Radar must also be considered in two categories, pulse-doppler and synthetic aperture. The former uses the motion of the target to distinguish it from the background, whereas synthetic aperture radar achieves its high resolution by integrating a large number of reflections received by a moving radar from a stationary target. The faster the target is moving, the better for the Doppler radar, but the worse for the synthetic aperture radar.

The probability of detection needed to fulfil a mission depends on what that mission is. If six bombers intrude, definite identification of three of them should suffice to trigger the warning system. Apprehension of one out of ten drug running attempts would eventually decimate the activity. But if an intruder knows that the surveillance never works at night, he may be able to avoid it every time.

Table B summarizes the capabilities and limitations of the various sensors and platforms, and of data processing for the different types of surveillance.

TABLE B

Suitability of Different Sensors for Various Functions

FUNCTION	SENSOR			DATA PROCESSING
	VISUAL	INFRARED	RADAR	
• Detection and tracking of aircraft	Only at very short ranges. Unable to penetrate weather and darkness.	Spaceborne IR promising. Unable to detect below clouds. Airborne IR tactically very useful, but weather limited.	Ground based very good against high targets within LOS. Low targets within FOV for short time. Airborne (AWACS) very good against high and low targets. Difficult to detect moving targets with Spaceborne SAR. Spaceborne PD has potential but requires very high power levels.	Modern technology is adequate. Data can be transmitted electronically to a remote location for display and control. Maximum data processing at the sensor location preferred.
• Detection and tracking of cruise missiles	Target too small and too low for useful visual detection or tracking.	Potential for airborne or spaceborne, but weather limited.	Target too low for effective tracking from the ground. AWACS has potential with PD. Spaceborne potential with PD but requires very high power levels.	Detection more of a problem than data management.
• Detection and tracking of long range ballistic missiles	Airborne optical adjunct for late phase tracking and discrimination.	Spaceborne IR very effective during boost phase. Spaceborne LWIR promising for mid course tracking.	BMEWS effective for high altitude, mid-course portion of trajectory. Ground based radar good for discrimination and terminal phase.	Could be saturated by decoys or have communications blacked out by nuclear detonation.
• Air traffic control	Not useful.	Spaceborne IR has potential but only when targets are above clouds.	Ground based radar satisfactory where available but limited by LOS. AWACS could supplement but not continuously. Spaceborne SAR may have potential but PD requires high power levels. Greatly aided by IFF beacons.	Modern technology is adequate. Information may be relayed to a remote location for display and control.
• Search and rescue	Visual search is primary means for final detection of a downed aircraft or ship in distress.	Spaceborne and airborne IR has potential but weather limited.	Ground based radar is very useful to provide latest position when available. Spaceborne radar would greatly assist depending on revisit times.	Modern technology adequate. Information can be relayed for control at a remote location, as now successfully done with ELT and SARSAT.
• Drug interdiction, illegal immigration control, and fisheries surveillance	Airborne surveillance useful over limited area.	Airborne IR would be a valuable addition to visual at night, but subject to weather restrictions. Spaceborne IR has potential, but subject to weather and false alarms.	Shore and ship-based radar useful when available. AWACS very effective when located in right area. SAR in aircraft or satellite has potential against boats and perhaps small aircraft.	Would require information similar to ATC flight plans on ship movements. Identification difficult.
• Agricultural, forestry, ice reconnaissance, oceanography, prospecting, pollution detection, surveying, weather	Airborne and spaceborne photography very useful. Time delay to receive information is acceptable.	Airborne and spaceborne multi-spectral imaging very useful. Commercial applications.	Airborne and spaceborne very useful with high resolution imagery radars. Able to penetrate weather.	Highly developed. Great resolutions impose significant demand on processing capacity.

One of the more demanding functions is the defence and security role of detection and tracking of aircraft. In this case, visual sensors are of only limited use and then only at short ranges in clear weather during daylight hours. Infrared sensors have more potential for this role, and space based infrared sensors (Teal Ruby) are being considered as a possible solution to the wide-area surveillance problem faced by NORAD in the Arctic. These sensors are not able to provide all-weather coverage below cloud and will thus suffer significant periods of interruption. Airborne infrared systems have considerable tactical appeal but are useful only at short ranges and are weather limited. Neither infrared nor visual sensors have an inherent capability to detect moving targets against a non-moving background.

Radar is the most capable sensor for this role based on its all-weather, day-night, long range capability. Ground-based radar, due to its virtually unlimited capability for power generation and unrestricted antenna size, is very useful against higher altitude targets at great ranges (provided that the target is within its line of sight). Low level targets, particularly those moving at high speeds, are within the ground based radar's field of view for only a very short period of time. Over-the-horizon radars, utilizing energy reflected from the ionosphere, have demonstrated a capability to detect a variety of large and small moving targets at all altitudes at great ranges, however, this technology does not function well in the Arctic due to interference from the aurora borealis.

Airborne radars, such as that found in the Airborne Warning and Control System (AWACS) aircraft are very good against both high and low level targets, enjoy a significantly improved line of sight, and demonstrate considerable flexibility. However,the size and power capability of components is limited when compared with ground-based systems. Spaceborne radars have far smaller line-of-sight restrictions than either ground or airborne, resulting in a very large field of view. However, size and power are very limited, and component cost is extremely high due to the inaccessibility of the components after launch and the consequent need for extremely high reliability.

The high power levels required, particularly for pulse doppler systems designed to detect small moving targets, are difficult to generate in space without recourse to compact nuclear reactors. The synthetic aperture technique, which is well suited to ground imaging, requires lower power levels (within the capability of solar arrays), but the ability to accurately detect targets moving at more than a few kilometres per hour is not well developed.[51] Should this capability be proven feasible in the future, a system with the ability to switch between the functions of ground imaging and moving target detection would be ideally suited for Canadian requirements.[52] Modern technology, in large part pioneered by Canadian industry, appears adequate to handle the data processing requirements generated by this task. Information can be electronically transmitted from a remote location to a central processing facility (as currently done for the North Warning System), for display and control. The more initial processing that can be done at the sensor location, the better, as this reduces the vulnerability of the communications link and the physical quantity of data to be carried. This is somewhat more difficult to achieve on orbit.

The role most demanding of sensor technology at this time, is the detection and subsequent tracking of cruise missiles. A system capable of performing this very difficult task would be able easily to meet the requirements of other functions.

The uncertainty facing anyone rash enough to forecast the cost of an enormous programme involving the first major application of new surveillance technology have been well demonstrated by AWACS and OTH radar. Both programmes were initiated in the 1960s, encountered unforeseen setbacks, and eventually cost an order of magnitude more than originally expected. Today a single AWACS aircraft costs approximately $US 200

---

[51] At this point, moving targets are processed by SAR, but end up being displaced in position when displayed. If the return is moving with a relative velocity of more than a few kilometres per hour, it will be badly misplaced with respect to the remainder of the image.

[52] G.N. Toandoulas, "Space Based Radar," *Science*, Volume 237, 17 July 1987, p. 257: This article states that both moving target indication and synthetic aperture modes can be incorporated into a space based radar sensor, with the mode being invoked selectively as the need arises.

million,[53] and about $2.3 billion has been spent on OTH-B (with only one station operational today).[54] Authoritative accounts of satellite programmes usually (and wisely) avoid any reference to the costs.

However, for those who insist on some numbers it could be noted that the Canadian RADARSAT is budgeted for about $CDN 400 million (not including launch costs to be borne by NASA), and that the Swedish Space Corporation estimated the programme cost to provide a single satellite designed for monitoring multilateral agreements from space at over $US 400 million.[55] Any military programme is sure to require a constellation of satellites. One assessment of a space-based radar system for continental air defence estimated the cost of each radar satellite to be in the half to one billion dollar range. Continuous worldwide coverage would require a constellation of nineteen satellites, and intermittent worldwide coverage ten, while an experimental version for intermittent coverage of the polar regions could be provided with three.[56] In order to feel able to verify the INF Treaty and a proposed START agreement, the United States added a five-year programme for modernization of observation satellites costing $US15 billion.[57] These are indeed major undertakings.

---

[53] *Continental Air Defense: A Neglected Dimension of Strategic Defense.* Arthur Charo, Center for Science and International Affairs, Harvard, 1990. p. 83.

[54] *Ibid.* p. 75.

[55] "The New Hierarchy in Space", Michael Krepon, Chapter 3 in *Commercial Observation Satellites and International Security*, eds. M. Krepon, P. Zimmerman, L.Spector, and M. Umberger. St. Martin's Press, New York, 1990. p. 27.

[56] Continental Air Defense. *op. cit.*, p. 93.

purposes such as charting, and monitoring of agriculture, forestry, and environmental disasters or degradation.

If the expected reductions in the size of conventional armed forces in Europe takes place, and the improved nature of international relations persists for a few years, there will be less need to maintain substantial numbers of the Canadian Armed Forces in a posture able to react to adverse world developments on very short notice. But it will be necessary to retain the professional capability to understand, assess, operate, and maintain high-technology military systems and, to expand if and when the need arises in the future. A sensible method of doing this will be to procure and use equipment and employ the personnel for purposes that are of national importance, though possibly in support of security or other national requirements that are not strictly or even partially military, as long as they are sufficiently related to military roles to maintain the skills needed for a return to purely military roles. One family of tasks eminently suited for such tasks is surveillance.

At this stage in the rapidly developing technology of spaceborne and airborne surveillance, it is not possible to identify with any confidence exactly which capabilities should be sought, or which would be the best systems to purchase in order to fulfil the requirements. Even less is it possible to make worthwhile estimates of the costs of various candidate systems. A considerable gap exists between the present stage of knowledge and the engineering designs that would be needed before analyses of costs and effectiveness could be made. It is clear, however, that any system based in space is going to be very costly, with a billion dollars buying no more than one or two satellites.

In these circumstances there could be much merit in Canada's taking an experimental approach. As well as producing high resolution imagery of the surface of the earth, of great value for many purposes, primarily civilian, RADARSAT should provide essential experience in the operation of space-based synthetic aperture radar over the Canadian North. Parallel development of sensors able to detect small moving objects at long range could lead to an experimental spaceborne or airborne system designed to investigate cost-effective application for air defence and air traffic control.

To speculate for a moment, this could take the form of radar combining the techniques of synthetic aperture, already proven as a most effective means of obtaining high-resolution imagery of stationary objects on the ground, with pulse-doppler, so far the best method of detecting small moving objects on or above the surface of the earth. If both modes of operation could be obtained in one satellite of bearable cost, the return for many national purposes could be most satisfactory. But it appears probable that provision of continuous early warning of the approach of aircraft or missiles would require a considerably greater number of satellites than would be needed for good coverage of ground imagery.

Alternatively, it could prove feasible to equip aircraft less costly than AWACS with radar able to provide useful surveillance of both fixed and small moving objects, supplemented by electro-optical sensors with great capabilities when allowed by cloud and weather. Such a system would have the advantage of portability to any part of the globe. However, aircraft are better adapted to provision of intermittent than of continuous cover over a large area.

Even after more experience and knowledge has been obtained, rather than seeking early procurement of a complete system capable of continuous warning, it could be more prudent to begin with a developmental deployment. Intermittent warning has some value for deterrence, the experience would contribute knowledge needed for making a later decision regarding a complete system, and the programme would develop Canadian expertise in the technology of the future.

A single satellite orbiting at low altitude and able to sweep a path no more than a few hundred km wide will not be able to cover all of Canada (let alone the approaches) in a period of less than several days. Also, since it may be impossible to rectify malfunctions in an orbiting satellite, reliability demands the presence of more than one. Consequently, any attempt to provide reliable and continuous space-borne warning of attack coming by aircraft or cruise missiles must inevitably involve a constellation of satellites. The number required in the constellation depends on the design of the satellites, the area to be surveyed, and on the degree of tracking demanded, but is likely to be around eight, ten, twelve, or more very expensive vehicles, probably using pulse-doppler

PART V - CONCLUSIONS

Surveillance of Canadian territory and the approaches to it is needed for several different purposes. Electro-optical and radar sensors of several different types can take effective parts in such surveillance. There are advantages and disadvantages with each type of sensor, and for the placing of the sensors in ground installations, in aircraft, and in space. The effectiveness of surveillance is enhanced by the use of a variety of sensors placed in a complementary fashion on the ground, in the air and in space. It is unlikely that the future surveillance needs of Canada can be completely met by a single type of sensor or a single deployment method.

The most demanding types of surveillance are for the purposes of defence. Reductions in the stockpile of strategic nuclear weapons will not remove the need to preserve stable deterrence, and this requires reliable early warning of the approach of ballistic missiles, bomber aircraft, or cruise missiles towards North America. Maintenance of the Canadian contribution to this type of surveillance is clearly a role for the Armed Forces. It seems probable that the systems to provide warning of the approach of ballistic missiles, deployed and operated by the United States, will not need participation by Canadians. However the application of modern methods of surveillance to the functions of verification of arms control agreements and to peacekeeping could involve participation of Canadian Forces personnel far from North America.

The equipment, personnel, and organizations able to carry out surveillance for defence are also capable of performing other tasks of national importance. Some of these such as search and rescue, air traffic control, interdiction of drug traffic, and fisheries regulation involve surveillance and tracking of aircraft and ships, which should be a task added to that of early warning against military attack. Many of the aspects other than surveillance may be better managed by civil authorities.

Depending on the equipment procured and the organizations employed to carry out these roles, which are primarily ones of detecting and tracking aircraft and ships, it may be possible to take advantage of the same vehicles, organizations, and sensors (perhaps with some modification or addition) to carry out needed surveillance of other sorts, for radar, and possibly with their electrical power produced by a small nuclear reactor. A highly sophisticated data processing system would also be necessary. In view of the vital worldwide purpose of the system, and of its inevitably very heavy cost, this would appear to be more suitable for an international than a Canadian undertaking. However, the launching of even one or two satellites would provide some capability, with the potential of subsequently becoming part of a larger system.

For the early warning role, a choice would be available between coverage of all of the globe (i.e. inclinations of nearly 90° for at least some of the constellation) or optimum coverage of a selected barrier line. If this line were around the parallel at 70°N, the latitude of the North Warning System, excellent coverage could be obtained with a smaller constellation, at the expense of poor (or no) coverage north of the barrier.

The most valuable peacetime use of the capability provided by a defence system able to track aircraft continuously would be for air traffic control over vast areas in which no such service exists today. There would also be great potential for search and rescue, fisheries surveillance, and drug interdiction.

It does not seem feasible to provide continuous reliable warning against cruise missile attack, or effective worldwide air traffic control, by any means other than radar deployed in a constellation of satellites. But if this monumental task is undertaken, there seems every prospect that a number of very valuable additional services could be provided as well. This should certainly be the case if it proved feasible to operate the radar in a synthetic aperture mode, producing high resolution images of the ground, as well as in a pulse doppler mode, for detection and tracking of small fast-moving targets. It may be possible to add electro-optical sensors to the radar, providing many additional forms of surveillance for civil as well as military purposes.

A Canada that was determined to be able to participate in the high technology of the next century could undertake a somewhat less ambitious mid-term plan, one within its own financial capabilities. This could be to pursue the RADARSAT project for a satellite with a powerful high-resolution synthetic aperture radar, and at the same time to press research and development of advanced radar and electro-optical technologies suitable for deployment in aircraft, and designed for the detection of small moving targets. Something smaller than AWACS, with a radar taking advantage of the remarkable signal processing techniques of the 1990s, and with advanced electro-optical sensors, could play a part in North American defence, for which an inadequate number of AWACS are assigned. Such an aircraft would also be of great value for arms control verification and peacekeeping abroad, and the gamut of peacetime applications in Canada. Another area in which research should be pursued is in the possible application of Over-the-Horizon radar inside of the Auroral Zone. If successful, this would offer the possibility of detecting cruise missiles in the Arctic.

When more is known regarding engineering feasibilities, and enough evidence has been accumulated on which to make realistic cost estimates, it should be possible to come to a major decision about a programme for surveillance of Canadian territory and the approaches thereto. The decision will affect the extent to which the Canadian Armed Forces and Canadian science and industry will participate in the aerospace technology of the future.

ANNEX A

Over-The-Horizon Backscatter Radar

Over-the-horizon radar has evolved to meet the requirement for very long range detection of airborne targets approaching the North American continent.[58] OTH is modified with the term 'backscatter' (OTH-B) when the radar receiver is located within a few hundred kilometres of the transmitter. In some versions, known as frontscatter, the energy is detected at a remote location. The US Navy is developing a relocatable-over-the-horizon radar, known as ROTH, based on the same principle but capable of being moved, although it might take many days or weeks to assemble in a new location.[59] OTH-B is currently entering operational service with the United States Air Force but has been providing information that has been operationally useful for a significant period of time.[60]

The principle of operation is that radar energy of the correct frequency, when aimed at the ionosphere, will be reflected back to earth at a far greater distance than the ordinary line of sight. This energy when striking targets in the beam will be reflected back to the receiver by a similar route. The doppler principle can be applied to reflections from OTH-B to allow the system to discriminate moving targets against a fixed background. Due to the very low frequencies and thus long wavelengths employed, the accuracy of tracking small targets is not high, therefore, this system while good for large area surveillance, would be of less use for accurate tracking. Also a result of the very long wavelengths involved, the structures associated with OTH-B antennas are very large and the transmitting and receiving units must be widely separated on the ground to avoid interference.

The height of the ionosphere varies by night and by day, and the frequency used by the OTH-B must be altered within the high-frequency band, to accommodate this. This results in performance changing with the time of day, as well as with unusual activities in the ionosphere. This dependency on a relatively stable reflecting layer inhibits the utility of OTH-B in the Arctic regions where the ionosphere is particularly unstable in a large doughnut-shaped area known as the Auroral Zone. However, it is possible that an OTH-B system could be made to operate inside this Auroral Zone, in an area centred on the magnetic pole in northwest Greenland and with a radius of about 2000 km.

---

[58] *Jane's Weapon Systems 1988 - 1989*, London: 1989, pp. 302-303.

[59] "Raytheon Wins Relocatable Radar Contract," *Defense News*, 8 January 1990, p. 15.

[60] "Maine OTH-B Completes Development..." pp. 52 - 53. This article reports that the system in Maine has been able to detect a very small private aircraft over Puerto Rico, and has demonstrated some capability against the cruise missile, although any attempt to upgrade the system to improve this performance would be very costly. In addition, it cites an example whereby the Maine system was able to assist Canadian Air Traffic Control to locate a Cuban airliner that was in distress over the North Atlantic on 28 January 1990.

An OTH-B radar covers a tremendous volume of airspace. For example, the system in Maine covers a region from 900 to 3300 km off the east coast of the United States providing a coverage volume of 5.4 million square kilometres - approximately 3% of the earth's surface.[61] The blind zone out to 900 km is a result of the requirement to bounce the energy off the ionosphere at a glancing angle and back to the surface of the earth.

---

[61] "Maine OTH-B ..." op. cit. p. 52.

ANNEX B

The Principles of Synthetic Aperture Radar[62]

Modern methods of digital signal processing have enabled great improvements to be made to the performance of radar. One of the most powerful of these, known as synthetic aperture radar, overcomes the limitation on angular resolution, which in a conventional radar is established by the size of the antenna, to which there are obvious practical limits, especially in an aircraft or space vehicle.

Synthetic aperture radar uses the motion of the vehicle on which it is mounted, thus taking advantage of the doppler effect. This is a phenomenon associated with wave motion radiated by a moving body, reflected by a moving body, or observed by a moving sensor. Relative motion between the source and the receiver causes the frequency to be changed, by an amount proportional to the relative velocity. A common example is the change in the pitch of the sound from the horn of a speeding railway locomotive as it passes the stationary listener. The doppler effect is observed with electromagnetic waves, so that a moving radar transmitting on a fixed frequency will receive echoes whose frequencies are slightly shifted, by amounts which depend on their relative motions as seem from the radar. If the radar beam is directed sideways to the direction of motion of the vehicle, stationary targets ahead of the radar will be seen as approaching it, while ones behind it will be receding. Only stationary targets exactly abeam of the radar will experience zero doppler shift.

Using the techniques of modern computers, the signals received by the radar are stored over a period of several seconds, during which the vehicle has moved through an appreciable distance, and many pulses have been radiated and echoes returned. By combining the series of pulses received from the same range, and keeping track of their doppler shifts, it is possible to determine the extent in the direction along the track of each reflecting target, with a precision very much better than could have been obtained with a conventional radar with the same antenna aperture. In fact, the resolution is better than that which could have been obtained using a fixed antenna as long as the distance through which the actual antenna was moved during the period over which the signals were integrated.

To match this great improvement in resolution along the direction of motion of the vehicle it is desirable to achieve comparable resolution in the direction across the track. Fortunately, this is not difficult, and can be accomplished either by using very short transmitter pulses or by employing a clever electronic technique known as pulse compression.

In this manner it has become possible to produce radar images of the ground (or the sea, or ice) that compete with photography in their ability to reveal fine detail, and their collection is not dependent on sunlight or clear air. And they have the additional advantage that the resolution is as good at long as at short range.

---

[62] Stimson, pp. 527 - 548.

ANNEX C

The Principles of Pulse Doppler Radar[63]

As described in Annex B, synthetic aperture radar exploits the doppler effect to obtain high resolution of stationary targets being observed from a moving radar. Another very useful exploitation of the doppler effect can be made in the observation of moving targets, such as aircraft, ships, or vehicles on the ground, which return echoes that are much smaller than those from the surrounding ground or ocean, especially when observed from above. For this application the platform on which the radar is mounted can be either stationary, or if it is moving, its motion can be compensated in the signal processing.

To measure range, a radar needs to transmit energy in short pulses. The shorter the pulse, the more precisely can targets at slightly different ranges be resolved. But to detect motion, the pulse must last long enough to observe any shift in the frequency away from that of the original transmitted pulse. As seen from a moving radar, the unwanted background is also moving, so what must be detected is the difference between the Doppler shifts of the small moving target and of the much larger background.

The eventual display will suppress all of the echoes from fixed reflectors, and show only the positions of those that are moving with respect to the background.

Because the reflections from small objects such as aircraft are usually weak, and because it is not possible to integrate the combined results of many pulses in the same manner as is done with synthetic aperture radar, pulse doppler radars intended to detect aircraft at long ranges require considerable transmitter power.

[63] Stimson, pp. 243 - 366.

ANNEX D

Spacecraft Power Requirements

In order for a spacecraft to function effectively on orbit, power must be provided to operate both the sensors on board and to maintain "housekeeping" functions, such as command and control and station keeping. There are two power generation technologies that have been applied to spacecraft and that have potential for application to future surveillance spacecraft. They are solar array-battery combinations and nuclear power. Nuclear technology is used to generate prime power in space through the use of radioisotope thermal generators (wherein heat is generated by the radioactive decay of a radioisotope like plutonium) or with compact nuclear reactors that generate heat and convert it to electricity either external to the core (thermoelectric) or internal to the core (thermionic).

The choice of sensor and level of performance required from that sensor determine the level of power that must be generated for a satellite.[64] It has been estimated that a space based air traffic control radar system employing pulse doppler radar technology to detect airliner size targets would require in the range of 100 KW of prime electrical power.[65] RADARSAT, an earth imaging satellite to be launched for Canada in 1994 will employ a synthetic aperture radar to detect relatively large targets on the ground and will require prime power in the range of 2.5 KW.[66] The power required for a radar to detect a range of targets are summarized in Table D-1.

Table D-1
Typical Power Requirements for Space Based Radar

Sea Traffic, Topographical, Weather	0.2 to 5 KW
Treaty Verification, Crisis monitoring, Sea Traffic	1 to 30 KW
Commercial Air Traffic	10 to 300 KW
Military Missiles and Aircraft	100 to 2000 KW

[64] "Perceived need for nuclear power on satellites," *SIPRI Yearbook, 1983*, London and New York: Taylor and Francis Ltd, 1983, pp. 459 - 463.

[65] M.S. El-Genk and M.D. Hoover, eds., *Space Nuclear Power Systems 1987*, Malabar, Florida: Orbit Book Company, 1988, p. 25.

[66] "Team of Canadian U.S. Firms ...," p. 111.

Table D-2 lists some satellites systems that have been placed in orbit or will be launched in the near future with the power levels required to maintain the satellite and operate the sensor.

Table D-2
Satellite Power Capabilities.[67]

Technology	Date	System Power (KW)	Radar Pav (KW)	Radar Pp (KW)
Soviet RORSATs (nuclear)	1971 – 1985	2 -3		
DSCS II, US Comm Sat (solar)	1971	.5		
SkyLab (Solar)	1973	12.5		
LES, US Comm Sat (nuclear)	1976	.15		
SEASAT (JERS-1) SAR (solar)	1978	0.624	0.06	1
COSMOS 1500, Soviet Side looking Radar (nuclear)	1983	.4	.03	100
RADARSAT, Canadian SAR (solar)	1995	2.5	0.8	5
Hubble Telescope (replacement solar array)	1995	5.0 (degrading to 4.3 KW after 5 years)		

Solar array-battery combinations have been the most frequently used space power systems since the 1970s, providing reliable and long-life electrical power in an output range from a few hundred watts to as high as 12.5 KW. Current plans call for the use of solar array-battery technology on the space station in the 37.5 KW to 75 KW range with growth anticipated as high as 150 KW[68] and perhaps reaching 300 KW with multiple arrays. Rechargeable batteries (normally nickel-cadmium) are required with solar arrays to provide power when the satellite goes into eclipse. Batteries entail very high weight penalties, for example, a battery capable of providing 40 KW of electrical energy would

---

[67] Skylab data from L.J. Cantafio, *Space-Based Radar Handbook*, (Norwood MA: Artech House Inc., 1989) p. 569. Hubble Telescope data from " BAe Tests Solar Arrays for Hubble Servicing," *Space News*, March 12-18, 1990, p. 9.

[68] Cantafio p. 569.

weigh approximately 2300 KG.[69] Thus, the biggest drawback of solar-battery technology is the high weight, and with launch costs averaging in excess of $6,000 per KG,[70] this becomes a significant factor.[71]

Nuclear power sources offer significant reductions in mass when power levels needed exceed a few 10's of kilowatts, and may be unavoidable when moderate to high levels of continuous power are required for an extended period of time.[72] The United States has launched a significant number of nuclear powered satellites since 1961, primarily radioisotope thermal generators. The Soviet Union has launched considerably more systems, using mostly small nuclear reactors. At the present time, the Soviets have flight tested a new type of thermionic reactor called the "Topaz" which produces about 10 KW of electrical power.[73]

Table D-3 compares the power levels available from the two technologies.

Table D-3
Satellite Power Technologies (> 1 year duration)[74]

Power Level	Technology
0.1 to 1 KW	radioisotope thermal generator and solar arrays
1.0 to 10 KW	dynamic isotope power systems and solar arrays
10 to 100 KW	nuclear reactors and solar
> 1 00 KW	nuclear reactors

[69] *Ibid.*, p. 573.

[70] "Funds Sought for Coil Gun Device," *Space News*, 15 - 21 January 1990, p 1.

[71] As another example, *Journal of Global Security*, Volume 1, 1989 p. 94: for a projected 100 KW system a nuclear reactor would weigh approximately 5000 KG, a solar panel about 10,000 KG and a chemical equivalent mass would be about 6 million KG.

[72] G.N. Tsandoulas p. 237.

[73] Daniel Hirsch p. 155.

[74] *Science and Global Security*, p. 94.

ANNEX E

Swath Width Limitations

The extent of the swath that can be surveyed from a moving sensor may be constrained by difficulties which depend on the sensor, as well as on considerations of line of sight.

The upper layers of the atmosphere allow good propagation of visible light in the absence of clouds, fog, rain, and dust, allow some wavelengths in the infrared band to propagate as well as or sometimes better than visible light, and are nearly transparent to the longer wavelengths used by radar. However, some absorption and blurring occurs at all of these wavelengths when the radiation has to penetrate a long distance, nearly horizontally, through the lowest and densest layers of the atmosphere.

Because of this fact, surveillance of targets at long ranges will be unsatisfactory when the line of sight from an airborne or satellite-borne sensor makes a very small angle with the surface of the earth. The practical limit is usually taken to be 3°. This limits the surveyed swath to a maximum range less than that established by the horizon.

Radar sensors suffer from another limitation, due to the enormous reflections returned by the earth itself. These are at their greatest when the line of sight from the radar makes a large angle with the surface of the earth, and fall off significantly when the radiation can glance off in a forward direction instead of being reflected back towards the transmitter. Consequently it is usually not useful to try to observe the ground (or objects flying over the ground) in the cone directly below the vehicle. The critical angle depends on the nature of the surface and on the clutter rejection mechanisms of the radar signal processing system, but is usually between 50° and 80°. This limitation provides a "nadir hole" underneath the vehicle, in which surveillance cannot be conducted. It does not apply to electro-optical sensors.

These two limitations are illustrated in Figure 4 for three satellite altitudes.

ANNEX F

GLOSSARY

Accessibility interval: The period required to obtain a repeat image of a point on the earth's surface. By using sensor offsets, it can be a much shorter period than the repeat interval or revisit time.

Active sensors: Devices that transmit and receive energy in some portion of the electromagnetic spectrum. The basic principle of operation involves transmitted energy illuminating objects in its path and the sensor subsequently detecting the echoes or reflections from that object (conventionally called a target) for the purposes of surveillance, detection, tracking or identification.

Apogee: The point in any non-circular orbit where the orbiting body is farthest from the earth.

Ballistic Missile: A pilot-less projectile propelled into space by one or more rocket boosters. Thrust is terminated at an early stage after which re-entry vehicles follow trajectories that are governed mainly by gravity and aerodynamic drag, with relatively minor mid-course and terminal phase corrections.

Ballistic Missile Early Warning System, BMEWS: A small chain of very large radars for the detection of ballistic missiles approaching North America from the general direction of the Soviet Union. Sites are located in Thule Greenland, Clear Alaska, and Fylingdales Moor in England.

Cruise Missile: An air-breathing, guided missile that uses aerodynamic lift to offset gravity and propulsion to counteract drag. It can be launched from aircraft (air launched cruise missile or ALCM), from a submarine or surface ship (sea launched cruise missile or SLCM) or from the ground (ground launched cruise missile or GLCM).

Detection: The ability to decide whether an object or activity of interest is present at a given location. In order for a sensor to detect the presence of a specific object, it normally requires a spatial resolution in the order of one half the physical dimension of the object.

Electromagnetic spectrum: The electro-magnetic spectrum represents the family of transverse waves made up of oscillating electric and magnetic fields which travel through a vacuum at the speed of light. The spectrum extends from the very low frequency long wavelength radio waves to the very high frequency, short wavelength gamma rays. While visible light, infrared, ultraviolet, laser, X-ray, etc., are all parts of the electromagnetic spectrum, acoustic energy (which is based on hydrodynamic pressure) is not. The relationship between wavelength and frequency is an inverse one - the longer the wavelength, the lower the frequency.

Forward Operating Location: Air bases in northern Canada where interceptors assigned to the North American Air Defence (NORAD) role can operate. Locations as far north as possible are chosen to increase the probability of intercepting aircraft attacking North America before they can launch cruise missiles.

Geostationary orbit: If it is desired to maintain a satellite stationary above a point on the earth, it must be placed in a geostationary orbit. To accomplish this, the satellite must be travelling east, in a circular orbit above the equator at an altitude of 35,870 km at exactly the same speed as the point on the earth's surface.

Grazing angle limit: That area at the far reaches of a satellite sensors field of view where atmospheric absorbtion prevents sufficient energy from reaching the sensor to permit detection.

Greenland-Iceland-United Kingdom Gap, GIUK Gap: A choke point through which Soviet submarines from their main operating bases in the Kola Peninsula could pass in order to attack NATO sea lines of communication (SLOC) between North America and Europe.

Ground Track: The area traced out on the earth's surface directly below a satellite as it orbits the earth. Because the earth rotates eastward at a constant rate of 15.04° per hour, the ground trace of a satellite appears to move westward.

Horizon: Generally the distance from the observer/sensor to the earth limb, as a line of sight. Since most sensors are limited to line of sight, this is indicative of the maximum range of surveillance of that platform at that position.

Identification: The ability to discriminate a specific object under examination from other objects of the same class.

Inclination: The angle of inclination is the angle formed between the orbital plane occupied by a satellite and the earth's equatorial plane. The inclination also corresponds to the highest (or lowest) latitude reached by a satellite. For example, a satellite in a polar orbit which passes over the north pole, would have an inclination of 90°, while a satellite in orbit over the equator would have an inclination of 0°.

Infrared: Infrared systems utilize that portion of the electromagnetic spectrum just below the wavelength of visible light. In most applications, they are passive and sense the characteristic radiation given off by objects due to their temperature. Although they can function in the dark, they are severely restricted by weather. Very small temperature differences, in the order of a fraction of one ° C can be detected.

Instantaneous Field of View: The area or volume being sensed at one instant of time.

Intercontinental Ballistic Missile, ICBM: A ballistic missile with a range of 2,800 to 5,500 km.

Low earth orbit: An orbit about the earth at an altitude of less than 5,600 km. A high earth orbit has an altitude above 5,600 km.

Nadir hole: That area directly under a satellite employing a radar sensor where the clutter is so severe that the system is unable to detect targets.

North Warning System: A chain of radars stretching across the northern area of North America from Alaska to Greenland, designed to warn of the approach of hostile aircraft or missiles. The North Warning System will eventually consist of 13 long range radars (11 in Canada and 2 in Alaska) and 39 short range unattended gap-filler radars to improve low level coverage.

Orbit: A body is considered to be in an orbit or path about the earth if it is capable of completing at least one circumnavigation of the globe before striking the surface. This implies that the body has been given sufficient energy to lift it above most of the atmosphere, where drag would cause it to decelerate rapidly, and that it has been accelerated in a suitable direction to a velocity able to sustain it above the earth.

Over-the-Horizon Radar: A very long-range radar, operating in the high-frequency band, designed to provide electronic surveillance of aircraft at extended ranges. OTH radar bounces energy off the ionosphere to ranges well beyond those achievable with conventional radars which are limited by the line of sight to the horizon. The echo returns to the receiver by the same path.

Passive sensors: Devices that monitor a portion of the electromagnetic spectrum searching for a characteristic emission from an object or a class of objects for the purposes of surveillance, detection, tracking or identification.

Perigee: The point in any non-circular orbit where the satellite is closest to the earth.

Period: The time required for a satellite to complete one orbit about the earth. Higher altitudes above the earth are associated with longer periods and slower velocities. The shortest possible period is about 89 minutes.

Pulse Doppler Radar: A pulsed radar designed to detect moving targets against a non-moving background by exploiting the frequency shift which exists whenever there is relative motion between the radar and target.

Radar: An acronym which stands for radio detection and ranging. Radar was fully developed as a useful military sensor system during the second world war and remains the most pervasive of the active surveillance, detection and tracking systems in use today.

Reconnaissance: The examination of an area to determine aspects or characteristics of the area or of activities of interest.

Repeat interval or revisit time: The period required for the spacecraft to return to the same sensing position.

Resolution: Spatial resolution is the ability to discriminate between two objects on the ground. A spatial resolution capability of 5 meters means that objects closer together than 5 meters will appear to the sensor as one. Normally, an increase in resolution implies a loss in the area viewed or field of view. Resolution may also be spectral; that is the ability to discriminate between specific wavelengths or between objects at slightly different temperatures, or it may be in velocity. The resolution of a sensor is the smallest interval capable of being detected by that sensor.

Satellite: A satellite is an object which is held in orbit about another object due to gravitational attraction between the two bodies. Satellites may be man made or natural. For example, the moon is a natural satellite of the earth.

Sensor: A device that can detect electromagnetic, acoustic or other energy emitted or reflected by an object at a distance.

Sun-Synchronous Orbit: An orbit whose plane remains at a fixed angle with respect to the sun throughout the earth's annual revolution about the sun.

Swath width: The distance from one side to the other on the earth's surface that a specific sensor is able to survey at one time.

Surveillance: An activity that involves maintaining a close watch over a specific area for the purposes of determining what activities are taking place within that area. Surveillance can be continuous or periodic depending on the type of activities of interest. Closer examination triggered as a result of surveillance would be defined as reconnaissance.

Synthetic Aperture Radar: A radar designed to enhance the resolution in the across track direction of the radar motion. It achieves this by storing the returned data for a period of time and through processing, synthesizes a very long antenna. Airborne and spaceborne SAR is used primarily for ground imaging.

Tracking: Once an object has been detected, tracking involves monitoring the subsequent course of the object. Tracking may be continuous, in which case the sensor must maintain constant contact, or it may be periodic, with the sensor revisiting the object to be tracked with sufficient frequency to be able to maintain a track of its movement.

Verification: The process of determining the degree to which parties to an agreement are complying with provisions of the agreement.