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SURVEILLANCE FROM SPACE:
A Strategic Opportunity For Canada

by George Lindsey

June 1992

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PREFACE

Working Papers, the result of research work in progress or the summary of a conference, are often intended for later publication by the Institute or another publisher, and are regarded by the Institute to be of immediate value for distribution in limited numbers -- mostly to specialists in the field. Unlike other institute publications, *Working Papers* are published in their original langauge only.

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CONDENSÉ

Les capacités extraordinaires et en croissance rapide de la technologie spatiale sont très prometteuses s'agissant des nombreux et précieux services que le Canada peut en retirer. Cependant, il sera nécessaire, pour définir une bonne politique nationale, de tenir compte de la situation géographique du Canada, de son alignement international, de son économie et de sa sécurité, étant donné que les applications de la technologie spatiale sont inextricablement liées à ces quatre facteurs dominants.

Le Canada a une superficie de dix millions de kilomètres carrés et une population de vingt-sept millions d'habitants. Presque tout ce monde vit dans des villes et travaille dans des usines ou dans des fermes sur les terres arables les plus facilement habitables qui forment une bande étroite le long de la frontière méridionale. Dans le reste des dix millions de kilomètres carrés, l'habitat n'est que très dispersé. On y pratique l'extraction minière, l'exploitation forestière, la chasse et la pêche. Les responsabilités et les intérêts nationaux canadiens s'étendent sur plusieurs autres millions de kilomètres carrés d'océans et de glace, qui eux sont totalement inhabités.

Le présent document a pour objet de montrer combien les observations, les images et les mesures effectuées depuis l'espace sont importantes et utiles pour le Canada pour quantité d'applications. Citons la surveillance de l'environnement, la défense, la vérification des accords de limitation des armements, le maintien de la paix, la navigation dans les eaux encombrées par les glaces, la surveillance du trafic aérien et maritime ainsi que des pêches, la lutte contre la contrebande de drogues et l'immigration clandestine, la gestion agricole et forestière, la météorologie et la surveillance des inondations et des incendies de forêt, la cartographie et la planification urbaine.

Tout ces éléments, regroupés sous l'appellation de «surveillance aérienne et spatiale», sont, rappelons-le, d'une importance vitale pour un pays aussi vaste et aussi

peu peuplé que le Canada. Une partie de la surveillance peut se faire par avion plutôt que de l'espace, et le document expose les capacités relatives des deux méthodes.

Pour plusieurs raisons opérationnelles et techniques, il est utile de séparer la surveillance en observation d'objets statiques et d'objets mouvants. Les techniques modernes permettent à présent aux capteurs électro-optiques et aux détecteurs radars de donner des images détaillées d'objets *statiques*. Bien des applications pratiques peuvent être réalisées avec une entière satisfaction à partir d'un jeu de ces images de haute définition, sans besoin d'être répétées. D'autres applications, cependant, demandent ensuite des observations répétées, mais seulement à des intervalles de temps assez éloignés (des jours, des mois, voire des années).

Pour d'autres applications encore, il est nécessaire de détecter et de suivre des objets *mouvants*, tels que des aéronefs, des missiles ou des bâtiments de surface. Cela pose des problèmes techniques, jusqu'ici résolus par une surveillance terrestre ou aérienne, mais pas spatiale. La surveillance d'objets mouvants pose un problème supplémentaire très délicat : elle doit être continue, sans quoi on perd leur trace et ne découvre pas leur destination. Les satellites placés en orbite terrestre basse passent au-dessus des cibles à très grande vitesse et ne survolent pas de nouveau la même région avant plusieurs heures, voire plusieurs jours. En conséquence, la couverture continue d'une région donnée pour la détection et la surveillance de cibles mouvantes ne peut se faire depuis l'espace que grâce à plusieurs satellites se relayant.

Il est possible de séparer encore la surveillance de façon utile, s'agissant cette fois des cibles *coopérantes* et *non coopérantes*. Cela vaut tout particulièrement pour les cibles mouvantes. Les applications les plus difficiles sont celles se rapportant à la défense et à la répression des activités illégales, puisque dans ces cas, les cibles sont à la fois mouvantes et non coopérantes. Pour la surveillance du trafic aérien et maritime coopérant, aéronefs et navires aplaniront probablement toute difficulté de pistage grâce aux radiophares et aux communications radio. Cependant, toute interruption prolongée de la surveillance risque fort d'être inacceptable.

L'investissement nécessaire pour placer une charge utile en orbite est important, mais les bénéfices éventuels sont si étendus que l'entreprise mérite le soutien de nombreux utilisateurs. Or, c'est là que les problèmes politiques et administratifs surviennent.

On pourrait s'attendre à une coopération et à une utilisation conjointe entre ministères du gouvernement fédéral, mais on bute sur deux énormes obstacles. Le cloisonnement rigide des mandats et budgets ministériels, farouchement policé par le Conseil du Trésor, est le premier. Le second, c'est la difficulté qu'il y a à coordonner les exigences (et la démarche institutionnelle) du ministère de la Défense nationale - plus peut-être d'autres organes mandatés pour s'occuper des contrevenants peu coopératifs - et celles des ministères civils qui entendent gérer les comportements par des règlements et des autorisations. La tâche de l'armée est plus difficile et onéreuse, mais si on l'entreprenait, ses installations pourraient s'acquitter d'une partie, voire de la plupart des autres aussi, à un coût marginal.

Les gouvernements fédéral et provinciaux, plus le secteur privé, pourraient, en conjuguant leurs efforts, partager éventuellement des tâches civiles. En revanche, en matière de défense et pour certaines autres fonctions, l'extension évidente serait un partage international avec des gouvernements alliés pour le financement, la coopération dans la recherche et le développement, la fabrication, le déploiement et l'exploitation.

Le Canada a donc un choix à faire. Les États-Unis sont le partenaire évident. Mais, étant donné tout ce que les Américains consacrent à leur propre sécurité et leur immense pouvoir économique et technologique, ce partenariat s'avérerait très inégal. Une coentreprise qui produirait un système de satellites tout à fait compatibles, dont quelques-uns appartiendraient au Canada, qui les exploiterait en tant que participant à part entière des opérations conjointes, tout en gardant la possibilité de s'en servir à d'autres fins s'il le souhaitait un jour, serait plus satisfaisante qu'une totale mise en commun des avoirs.

Qu'il agisse seul, en association avec les États-Unis ou de façon plus multilatérale, le Canada devrait déclarer la surveillance spatiale technologie stratégique et s'y livrer pour le bien de l'industrie, de la technologie, de la sécurité, des relations internationales et de la prospérité générale du pays.

EXECUTIVE SUMMARY

The extraordinary and rapidly developing capabilities of space technology offer great potential for the provision of many valuable services for Canada. However, in order to arrive at a successful national policy, it will be necessary to take into account the circumstances of Canada's geography, international alignment, economy, and security, since the applications of space technology are inextricably related to all four of these dominating factors.

Geography presents twenty-seven million Canadians with ten million square kilometres of land. To the east is the Atlantic Ocean, and the sea routes to Europe. To the west is the Pacific Ocean and the sea routes to Asia. To the north are the empty Arctic wastes, and the great circle routes for aircraft and intercontinental missiles between North America and most of the other important centres in the Northern Hemisphere. And to the south is the United States, at once the world's only superpower, a friendly ally, and an economic giant capable of formidable if not ruthless competition and dominance.

Nearly all of the twenty-seven million Canadians live and work in their cities, factories, and farms in the most easily habitable and arable land in a narrow strip clinging to the southern border. The rest of the ten million square kilometres of land has only widely scattered settlements, occupied with mining, logging, hunting, and fishing. Canadian national interests and responsibilities extend over another several million square kilometres of ocean and ice, on which there are no inhabitants at all.

This wide and uneven distribution of people and economic activity makes communication and transportation extraordinarily important for Canada. In the nineteenth century Canada opened her West with railways and the telegraph, and built sea trade with Europe. In the twentieth century she built roads, air transport, and telephone, radio, and television networks. And very soon after it became possible, Canada was one of the first countries to exploit space for long-distance communications.

So far, the priority for Canadian space projects has been on telecommunications and scientific research, with very satisfactory results in both fields. However, the thrust of this paper is to point out the importance for Canada of the observation, imagery, and measurements that can be made from space, for purposes useful for a host of important Canadian applications. Amongst these are environmental monitoring; defence; verification of arms control agreements; peacekeeping; navigation in ice-strewn waters; control of air and sea traffic, of fisheries, and of illegal importation of drugs or immigrants; agricultural and forest management; forecasting and monitoring of floods and forest fires; cartography; and urban planning. We lump all of these under the general heading of "overhead surveillance," and reiterate their vital importance for a country as extensive and sparsely populated as Canada. Some of the surveillance can be done (quite a lot is being done) from aircraft rather than space, and the paper outlines the relative capabilities of the two types of platform.

One very far-sighted Canadian project of this nature is under way today with RADARSAT, a surveillance satellite to be equipped with synthetic aperture radar, with its launching planned for 1994. However, it is not intended to use RADARSAT for many of the applications outlined above, and many of them could only be satisfied by a constellation of several satellites, or by satellites with different sensors. RADARSAT will be an excellent beginning, unless it joins the lengthening list of victims of the government's financial cutbacks. But the opportunities to serve the nation's needs will call for more than one satellite with one type of sensor.

Canadian expertise in surveillance radar has been built up through hands-on experience gathered over years with airborne platforms, accompanied by development and operation of electro-optical sensors, equipment for data transmission (both air-to-ground and space-to-ground), and for the subsequent complete processing and analysis of the information. The technological knowledge needed to design, build, and operate space surveillance systems exists in Canada today.

For several operational and technical reasons it is useful to divide surveillance into observation of stationary and of moving objects. Modern technology now allows both electro-optical and radar sensors to produce finely detailed images of *stationary* objects. Many of the practical applications can be completely satisfied with one set of such high-definition images, and do not need to have them repeated. Some other applications do need subsequent repeated observations, but only at fairly long intervals (days, months, even years). These are the type of applications for which RADARSAT should be ideal.

For other applications it is necessary to detect and track *moving* objects, such as aircraft, missiles, or surface ships. This poses difficult technical problems, so far solved for surveillance from the ground and from aircraft, but not from space. Tracking of moving targets poses an additional and very demanding requirement, in that the surveillance needs to be continuous, or else the track and the destination of the moving targets will be lost. Satellites in low earth orbit pass over any one target at a very high speed, and do not revisit the same area for a period of some hours, or even days. Consequently, continuous coverage for the detection and tracking of moving targets over a specified area can only be accomplished from space by a phased constellation of several satellites.

A further meaningful division of surveillance can be made, between *cooperating* and *non-cooperating* targets. This is particularly relevant to moving targets. The most difficult applications are those for defence, and for control of illegal activities, since in these cases the targets will be both moving and non-cooperating. For control of cooperating air or maritime traffic, the aircraft and ships are likely to ease any difficulties in tracking them by using radio beacons and voice communication. However, it will probably not be acceptable to have long intervals during which surveillance is broken.

It seems evident that any system capable of this most difficult task of tracking non-cooperating moving targets will also be able to track moving targets which do cooperate. And an extremely cost-effective exploitation of an expensive constellation of satellites, with their orbits tailored for surveillance of the areas of most interest to Canada, would be accomplished if it were also capable of producing high-definition imagery of stationary objects, whether by adaptation of synthetic aperture radar or by addition of electro-optical sensors. Such combined capability should prove extraordinarily valuable even if the temporary surveillance of a limited area for high-definition imagery of stationary objects required a brief suspension of surveillance of moving objects.

This possibility illustrates the dilemma of the economics of space technology. The investment necessary to place any payload in orbit is large. Adding payloads, and especially adding additional satellites, multiplies the investment. But the potential benefits are so widespread that the enterprise deserves the support of many users. And here is where the political and administrative problems arise.

Cooperation and joint use could be expected among departments of the federal government. But here two formidable obstacles are encountered. One is the rigid compartmentalization of departmental mandates and budgeting, fiercely policed by the central Treasury Board. The other is the difficulty of coordinating the requirements (and institutional approach) of the Department of National Defence, perhaps along with other agencies mandated to deal with non-cooperating transgressors, with those of civil departments who expect to manage behaviour through regulation and licensing. The military task is the more difficult and expensive, but, if it were to be undertaken, its facilities might be able to do some, or most of the others as well, at a marginal cost.

Another stage of potential burden-sharing for the civil functions could be provided by joint efforts of the federal and provincial governments, and the private sector.[1] But for defence and some of the other functions the obvious extension is to international sharing among allied governments, for financing, cooperation in research and development, manufacture, deployment, and operation.

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[1] This has been done for RADARSAT.

Here Canada has a choice to make. The obvious partner is the United States. But the American dedication to its own national security and its huge economic and technological power would make it a very unequal partnership. Moreover, the worldwide capability of a constellation of advanced space surveillance satellites, together with the global interests of the United States, could present a situation in which the US elected to employ the system for purposes with which Canada did not wish to be associated, or which denied the use of the system for purposes for which Canada wished to apply it. More satisfactory than a complete pooling of assets would be a joint enterprise to produce a system of completely compatible satellites, a few of which would be owned and operated by Canada as a full participant in joint operations, but which would permit Canada to divert them for another purpose, if they should ever feel this to be desirable.

Whether it is done alone, in partnership with the United States, or on a more multinational basis, Canada should declare space surveillance to be a strategic technology, and pursue it for the benefit of the industry, technology, security, international relations, and general prosperity of the nation.

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I CANADA'S GEOSTRATEGIC SITUATION

With its vast area, uneven distribution of population, inhospitable climate, long coastlines on three oceans, and dependence on foreign trade, the internal and external activities of Canadians are heavily influenced by geography.

The early development of the country depended on transportation, beginning with overseas shipping and inland waterborne communications, followed by railways, roads, and air links. The harsh climate and great distances caused habitation to be strung out along the southern border. Physical movement of mail and commercial products was followed by extensive development of telegraphic and radio communications, and by television.

The space age has brought new capabilities to solve problems posed for Canada by her geography. The new potential that was first exploited was for telecommunications. Orbiting satellites now allow radio communications (including television) to be relayed between locations anywhere on the earth's surface, without having to depend on wires, submarine cables, intervisible microwave towers, or variable reflections from the ionosphere. The benefits are worldwide, but particularly valuable for Canada, with its great distances, difficult terrain, problems with northern magnetic storms, and dependence on overseas communications.

While economic transportation is not going to be provided in space vehicles, terrestrial transportation has been significantly improved by new services made possible by satellites. These include reliable communications to ships and aircraft, precise indication of position (irrespective of visibility), much improved weather prediction, reporting of ice conditions, and production of accurate maps and marine charts. Search and rescue, problems related both to transportation and to Canadian geography, are aided by devices in satellites.

A third general area in which space technology has brought immense new capabilities is in surveillance of the earth's surface and the multifarious activities on its land, on and in its seas, and in its atmosphere. Again, the characteristics of our geography made these capabilities particularly valuable for Canada. The purpose of this paper is to discuss space surveillance over and for Canada, including an account of what could be done, as well as offering suggestions as to what should be done.

In addition to the three invaluable services of telecommunications, transportation, and surveillance, space has provided startling new means of conducting scientific research in many fields, especially those related to earth sciences and astronomy. Many of these projects are basically international in character. Canada has played a very considerable part in such activities, but, as for telecommunications and navigation, they are not the subject of this paper. It is about surveillance.

II CANADIAN SPACE PROGRAMMES

The first major Canadian initiative in space was directed towards a problem of special significance to those wishing to communicate in or across the northern latitudes, in which ionospheric disturbances interfere with long-distance wireless transmissions. Canada had been probing the ionosphere from below, sending up radio signals and observing their reflections from various ionized layers at different times of day and in different phases of the solar sunspot cycle, and also launching instrumented rockets and balloons up to high altitude. The Alouette satellites orbited well above the ionosphere, and carried "topside sounders" which transmitted signals downward instead of upward. This and succeeding programmes increased the understanding of the structure of the ionosphere and its effect on radio transmissions of different frequencies and under different conditions.

In 1962, Alouette I made Canada the third nation to have a satellite in orbit. The programme was a joint effort with the United States, with the Canadian Defence Research Board designing, building, and financing the satellite, while NASA provided the launch vehicle. Telemetry was collected by ground stations constructed by Canada, and by stations in networks operated by NASA and Great Britain. Starting with Alouette II, launched in 1965, Canadian industry was involved in the construction of Canadian satellites. The Alouettes were followed by two ISIS satellites, and by Hermes. These were collaborative programmes with the United States, and in the case of Hermes also with the European Space Research Organization. A primary objective was to obtain information needed for the development of technology for satellite communication.

The Alouette programme allowed Canadian scientists and engineers to develop an expertise in the design and operational control of ground readout stations as well as satellites, and led to the subsequent creation and operation of the Anik series of functioning commercial communication satellites. The earlier models were mainly of US design, with Canada undertaking an increasing role later. Telesat Canada is the major operator of Canadian domestic satellites, while Teleglobe Canada manages the Canadian participation in international communication satellite systems.

Canada has been very active in remote sensing, especially since the creation of the Canada Centre for Remote Sensing in the Department of Energy, Mines, and Resources. However, Canadian participation in remote sensing from space has been carried out with American LANDSAT, French SPOT, and European ERS satellites, rather than satellites designed or owned by Canada. Nevertheless, many of the techniques learned from the communication satellites, combined with experience acquired from a wide variety of projects for surveillance from aircraft, have enabled Canada to exploit space-based remote sensing by international cooperation (primarily with the United States) and also to design, manufacture, and sell space-related equipment of a total value well above the amount of money that has been invested in space by the government. In 1991 sales of Canadian space products and services amounted to about $350 million, nearly half of this in exports (mostly to the United States).

The best-known Canadian space products have been the STEM antennas which unfold in space, the CANADARM device for manipulating objects in space, designed for use in the American space shuttle, and for the Mobile Servicing System to be used for the assembly and maintenance of the space station, and ground terminals for receiving and processing information from both communication and remote sensing satellites. Substantial continuing progress is being made in the technology of collecting, assembling, harmonizing, combining, and analyzing the data obtained from a variety of sensors. Improvements are being made to the speed with which images can be distributed to users, and also to the ability to accumulate masses of archival data with ready systematic access.

Search and rescue following air or marine accidents has been greatly aided by SARSAT. Most aircraft and ships now carry an "Emergency Location Transmitter" which, in the event of a crash, or if triggered by the crew, transmits a radio signal which can be detected by a satellite. Information including the approximate position of the source is relayed to the ground. The SARSAT programme is jointly conducted by USA, Canada, France, and Russia[2]. The spaceborne device is small enough to be added to the payload of satellites primarily devoted to other roles (such as meteorological observation). SARSAT has been instrumental in the rescue of a large number of survivors of downed aircraft and of accidents at sea.

In the field of scientific research the principal Canadian contribution in recent years has been to take a small part in the American astronaut programme and space station, including biological research in support of maintaining astronauts in space. Canada is a major participant in the development of a mobile servicing centre to support the operation of the space station, and is planning experiments on methods of fabricating new materials in conditions of near-perfect vacuum and zero gravity, as well as making observations of several kinds from above the earth's atmosphere.

The two Canadian projects which should put new satellites into orbit during the next few years are RADARSAT and MSAT. The former promises to be a pioneer venture in civilian all-weather remote sensing, and the latter to extend long-distance commercial communication to mobile terminals small enough to be carried in ships, aircraft, or motor vehicles. It is to be hoped that these very promising but also expensive projects escape the governmental cost-cutting measures that have cancelled other major imaginative Canadian engineering and scientific initiatives.

Apart from space programmes in which Canada has some degree of ownership or management, benefits of very great value are obtained by subscribing to the services of foreign or international commercial communication satellites, from weather forecasting dependent on meteorological satellites, from military intelligence gathered from satellites and provided to Canada by allies, and from the information being collected by scientific satellites. Others are being added, such as the navigational information from the American NAVSTAR GPS system. Many services can be obtained without having to own or operate a national system.

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[2] The Russian model is known as COSPAS.

III FUTURE CANADIAN INTERNATIONAL ALIGNMENTS

The purpose of this paper is to examine what Canada should do in space surveillance in the future. We look at the mid-term future, whose problems will have to be faced by a federal government successor to the one we have in 1992, in a world very different from the one of the past several decades.

Changes in global security and economics are likely to alter Canada's relationships with other countries, in ways that will influence our decisions regarding surveillance from space.

For the last five decades our policy for security has been based on alliance with more powerful countries, opposing the threats of the Axis powers in World War II, and soon after that from the Warsaw Pact. With the dissolution of the Warsaw Pact and the USSR, this threat has lost its urgency (although the huge arsenal of weapons is still in existence, and is distributed among states whose stability and viability is far from assured). In the 1990s the major threats to security appear to reside in proliferation of nuclear, chemical, and biological weapons, of ballistic missiles, and in the accumulation of large stocks of more conventional modern armaments by nations or sub-national groups seeking expansion, realignments of states or boundaries, or redress of past grievances in an unstable world.

While there does not seem to be any immediate prospect of these weapons being directed against Canada, the regional upheavals and enmities in many parts of the world make continuing military violence all too probable, unless effective international stabilizing measures can keep it contained and controlled. Canada has been an active, influential, and effective participant in these international endeavours, such as arms control and peacekeeping, and will probably wish to continue so to behave in the future. Space surveillance is likely to have a significant role in these activities.

The world's economic situation is also in the throes of change. Past efforts to improve prosperity in the Third World have not been very successful, and now the First and Second Worlds are suffering from widespread bankruptcies, unemployment, and recession. Competition among rival economic blocs may cause barriers to be erected which will inhibit international trade, and replace cooperation by bloc-to-bloc economic conflict. Leadership and success will be increasingly dependent on competence in advanced technology. Extremely reliant on both exports and imports, Canada is dangerously vulnerable to such developments, especially since about three-quarters of her trade is with the United States, and few of her exports are products of advanced technology.

Looking to the future, Canada would seem to have three basic choices for her linkages in security and in economics. One would be to seek a maximum of independence, a second would be to integrate as closely as possible with the United States, and the third would be to maximize multilateral relationships.

Each of these "pure strategies" has its advantages and disadvantages. Isolation implies rejection of allies for defence, and minimization of foreign trade. It is most unlikely that the United States would tolerate a huge weak northern flank astride the great circle paths to America from most of the centres of power in the northern hemisphere. The US would oblige Canada to choose between a much strengthened Canadian-manned and financed defence over its own territory and off its three coasts, or else acceptance of American installations and operations which would negate the drive for increased Canadian sovereignty and independence. Canadian influence in the United Nations and other fora of international relations would decrease. Further, the high standard of Canadian living, which depends on export of raw materials and import of foodstuffs and high-tech equipment, could not be maintained.

Canadian defence and economics are already quite closely integrated with the United States, and the consequences for Canada have been, on the whole, very satisfactory. NORAD has worked well for security. The free trade agreement represents an important step towards closer economic integration. However, the close integration with American defence can produce the appearance of agreement or collaboration by Canada in policies and activities with which it would prefer not to be associated. Past examples include the Vietnam war, the SDI programme, some of the US activities in Central America, and some arms sales. Also, it is possible that Canada could be prevented from deploying some components of its increasingly limited armed forces for some future overseas mission because of an undertaking to keep them available for North American defence. In addition, the removal of trade barriers can limit the ability of Canada to retaliate for what it considers to be unfair practices in cross-border trade, sharing of fishing, fresh water, or other national resources, or in other commercial activities.

Carried to excess, a multipolar (non-aligned) strategy could deprive Canada of significant allies, and for security could have many of the disadvantages of isolation. It would have the attraction of counterweights to the powerful American presence. It could be advantageous in a world of free trade, presumably an objective of the GATT, but such a world has not been arranged, and the trend may be in the opposite direction, towards formation of rival trading blocs. In spite of some efforts towards a more worldwide distribution, only a quarter of Canada's external trade goes to countries other than the United States, and the high costs and low productivity of Canadian labour and consequent failure of Canadian industry to meet the prices of international competitors do not bode well for a policy of multipolarity.

Against this background of general considerations of security and economic relations, the same choices for international alignment are faced in the determination of Canadian space policy. For a country in Canada's precarious financial situation, and given the expensive and worldwide character of space technology, a policy of isolation would seem inappropriate. Even Japan, which began with a strategy of self-sufficiency in space technology, and has ample financial resources, has begun to buy technology and seek joint projects.

The most efficient and effective employment of space technology for North American defence and for commercial applications will likely come about through joint efforts of cooperation between the United States and Canada, and this is a strategy which could exploit and develop capabilities already present in Canada.

The worldwide nature of space surveillance makes multilateral exploitation attractive, both for security (through application to early warning, arms control verification, and peacekeeping), and for commercial and scientific use. The past success in the selling of Canadian ground readout stations, remote sensing and data processing equipment, and associated services, to many countries underlines the desirability of an aggressively multilateral approach.

When faced with stark choices, the usual Canadian reaction is to compromise, and this may well be the best solution to the problem under consideration. A space programme completely independent of the rest of the world would be both unfeasible and undesirable. But a combination of close cooperation with the United States with some degree of multilateralism would appear to preserve the most advantages for Canada.

The space surveillance that will be required for the defence and security of North America will be undertaken either by the United States alone, or by the USA and Canada in cooperation. The space surveillance that will be required for the support of worldwide peace and security could be provided by the United States alone, but the most probable and desirable arrangements are international, managed by regional groups or by the United Nations, and drawing contributions from many of the countries possessing space assets. Canada should be a prominent partner.

If Canada cooperates with the USA in a large programme to design, manufacture, and deploy a constellation of surveillance satellites adequate for the detection and tracking of non-compliant aircraft, ships, and possibly even moving ground vehicles, this would be able to serve the needs of North American defence, overseas military operations (whether of peacekeeping or active peace restoration), and of verification of arms control agreements. It would also have very great value for many other functions of both government and commerce, especially if the sensors were able to provide high-resolution imagery of stationary objects and make measurements needed for environmental monitoring as well as the tracking of moving vehicles.

However, just because of the many uses to which such worldwide surveillance could be put, and depending on the technical capabilities of the equipment, conflict could arise as to the tasking of the system when several users were seeking its services at the same time (or place). Whether the conflict were to be between surveillance over Canada or somewhere of more immediate urgency to the United States; or between a service to North American defence or to a UN operation elsewhere; or between an application for security or for commercial use; or between two commercial uses; a situation could arise in which Canada would be glad to have the right to use its part of the system for a purpose which it considered to deserve a higher priority than was being judged appropriate by the United States.

operations (whether of peacekeeping or active peace restoration), and of verification of arms control agreements. It would also have very great value for many other functions of both government and commerce, especially if the sensors were able to provide high-resolution imagery of stationary objects and make measurements needed for environmental monitoring as well as the tracking of moving vehicles.

However, just because of the many uses to which such worldwide surveillance could be put, and depending on the technical capabilities of the equipment, conflict could arise as to the tasking of the system when several users were seeking its services at the same time (or places). Whether the conflict were to be between surveillance over Canada or somewhere of more immediate urgency to the United States; or between a service to North American defence or to a UN operation elsewhere; or between an application for security or for commercial use; or between two commercial uses; a situation could arise in which Canada would be glad to have the right to use its part of the system for a purpose which it considered to deserve a higher priority than was being judged appropriate by the United States.

IV SPACE-BASED SURVEILLANCE AND CANADIAN TECHNOLOGY

Reference has been made to Canada's successes in the use of space for telecommunications and for scientific research. But more pertinent to this study is the technical expertise built up in connection with overhead surveillance. Much of this was associated with aircraft rather than satellites, but the techniques and equipment are qualitatively similar.

Nearly all of the Canadian research and development in overhead surveillance has been for the observation of stationary objects, and for applications other than defence. Since 1971 remote sensing has been sponsored by the Department of Energy, Mines, and Resources, primarily directed towards resource management. The sensors have been flown in Canadian aircraft, and in foreign satellites[3]. The main applications have been for mapping, forestry, agriculture, hydrological observation, ice reconnaissance, mineral exploitation, and environmental research and management. An important field of research and development has been in the improvement of techniques for combining data from different sources on a common accurately calibrated geographical base. Canada has become the world leader in the design and operation of ground readout stations located in many countries for the collection of data from satellites.

So far, the spaceborne sensors providing the data used in Canada have been electro-optical or microwave radiometric. Good results have been obtained with airborne radar, including sideways-looking SLAR and Synthetic Aperture SAR, and much is expected of RADARSAT, to be launched in 1994 with an advanced SAR.

If Canada is to be a serious competitor in high technology in the next decade, it must plan and invest now. In the rapidly growing field of space technology there is plenty of highly qualified competition in the United States, Russia, Europe (in the European Space Agency, and in France, Germany, Italy, the United Kingdom, Belgium, and Spain), Japan, China, India, and Brazil. If Canada does nothing, it will soon rank

[3] American LANDSAT, French SPOT, European ERS, and Japanese MOS and soon JERS.

with the rest of the Third World as a customer of those nations which possess the technology and offer it for sale on their own terms.

It will not be necessary to build booster rockets or a launch facility in Canada, since several countries are offering launch services on a commercial basis, and, once in orbit, there is no further dependence on the launch site. The opportunity to match the past engineering successes in telecommunications and remote manipulator mechanisms lies in space surveillance, where the necessary nucleus of expertise exists. But it will not be enough to pin everything on the single RADARSAT project, promising as it surely is today in 1992.

Space-based surveillance should be declared a "strategic technology" for Canada, and made the flag-bearer in a campaign to exploit the concentrations of qualified high technology that can still be found in the country, and make them truly competitive on a global scale. While they may never be able to match the biggest in the world, they can aspire to occupy important niches where the combination of specialization, familiarity with the conditions pertaining in northern latitudes, and hands-on experience allow us to win a place somewhere in the first rank.

For such a welcome breakthrough to be possible, it will be necessary to overcome the reluctance of large Canadian organizations and bureaucracies to pool their resources and cooperate in imaginative ventures that inevitably have a degree of technical and financial risk. One of the worst examples is presented by the federal government itself, in which each department is obliged to plan its activities and budgets within a closely defined mandate, fiercely policed by a central Treasury Board demanding guarantees of success with projects facing the uncertainties that are inseparable from pioneering undertakings.

If a satellite costing one billion dollars could (probably, but not certainly) perform services worth $100 million to each of twelve departments, which one could take the initiative and responsibility to procure it? In the recent past, departments have avoided cooperation with National Defence, for fear that there would be difficulties over security, costs would soar, programmes would be cancelled, or that the services which they need would be preempted on grounds of national security. In the language of systems analysis, everybody sub-optimizes within his own limited mandate, but nobody optimizes for the overall national good. Such piecemeal planning and administration misses opportunities for efficient coordination, and forces the Canadian taxpayer to pay for redundant infrastructure and unnecessary duplication. The recently created Canadian Space Agency is well placed to organize a coordinated policy, but it remains to be seen whether the different government departments can, or will, subordinate their own roles in a greater common cause.

To add to the difficulties, there is a technical segregation dividing the capabilities of space surveillance. The sensors available today provide excellent images of *stationary* objects, which can be repeated after intervals of several days. Such images are exactly what is needed for a host of civilian governmental and commercial applications. They are also very useful for many military applications (such as gathering of intelligence, making of up-to-date accurate detailed maps, and verification of arms control agreements). But for many other military applications the primary requirement is to detect and track *moving* objects, such as aircraft, missiles, and surface ships. For this purpose different sensors are required, and the observations must be repeated at very short intervals (if not continuously). Tracking of moving vehicles can also be of value to non-military users, for such applications as control of air or maritime traffic, detection of clandestine entry of aircraft or ships, fishery surveillance, or effective direction of search and rescue.

Thus, two types of users are (or should be) looking for two types of space surveillance. It could well be possible to design one satellite to perform both types of surveillance, but only if a concerted effort of research, development, and engineering were made towards that particular purpose.

A highly capable surveillance system generating a huge flow of information for many users for many different purposes would pose a daunting problem of data handling. Some of the information is likely to have a security classification, requiring that it be encrypted, or otherwise be kept unavailable to unauthorized users. Most of the users will prefer not to be inundated with a mass of information which they do not need. Some information will need to be presented continuously and with a minimum of delay (ideally in real time). Some may need to go directly to ships or aircraft. Some can be delayed without decreasing its value. Information from different satellites (perhaps also aircraft) will need to be combined without significant geographical errors being introduced. It may be advantageous to merge the data obtained from different sensors in various combinations.

All of these problems are suitable for solution using modern computer, data processing and communications techniques and electro-optical displays, and the appropriate expertise exists now in Canada. The technical problems are difficult, but there are Canadians who know how to solve them. With the proper domestic cooperation, Canada can compete with the rest of the world. But the political and administrative problems of getting all of these different users to cooperate in the creation and operation of a single comprehensive system may be even more difficult, perhaps beyond the capacity of the Canadian bureaucracies of the 1990s.

V GROUND-BASED, SEA-BASED, AIRBORNE, AND SPACE-BASED SURVEILLANCE

A comprehensive discussion of surveillance would need to include ground-based, sea-based, airborne, and space-based platforms for the sensors. It would also need to cover the different types of sensors, which include eyesight, photography, multi-spectral scanners (using infrared and ultraviolet wavelengths as well as those in the visual band), radar (including conventional, moving target indication, sideways looking, and synthetic aperture), lasers, passive radio frequency receivers and direction-finders, radiometers, spectrometers, magnetometers, and X-ray and gamma-ray detectors.

This paper concentrates on surveillance from space. However, in considering the proper applications for surveillance over Canada it is necessary to recognize which aspects of surveillance would be performed best from platforms other than spacecraft, and to take into account the principal characteristics and capabilities of the various sensors.

The choice of platforms for a particular role depends on a number of factors. Some of the most important are related to geometry and kinematics, governed by the area to be surveyed and the frequency with which observations are required. Others are related to the capabilities and limitations of the sensors. What is the practical limit of the range at which they can collect needed data, obtain useful imagery, or detect wanted targets, looking upwards into the sky, downwards towards land, or downwards towards the sea? Can they detect and track moving targets? To what extent does their performance depend on sunlight, moonlight, or atmospheric conditions? How much detail are they able to distinguish?

The most basic factor is the geometry of fields of view from a platform elevated above the surface of the spherical earth. This is discussed in the Annex, with examples given for observation from a ship, from a site on a mountain overlooking the sea, from an aircraft, and from satellites in Low Earth Orbit (LEO) and in Geostationary Orbit

(GEO).[4] [5] While the geometrical field of view of the surface of the earth is limited by the horizon (at which the straight line-of-sight from the elevated platform just grazes the surface of the earth), refraction in the lower levels of the atmosphere may bend rays enough to allow radar detection somewhat beyond the geometrical horizon, but because of absorption and scattering in the lower atmosphere the practical limit for useful electro-optical surveillance of the surface is normally much less than this.

Telecommunications

The antennas of radio transmitters are usually mounted on elevated sites, and their radiations pass through the atmosphere without significant absorption or scattering. Consequently a receiver in an elevated platform with a clear line of sight to the transmitter will probably be able to detect its signals out to very long ranges. Satellites in GEO designed for the collection of electronic intelligence can "hear" transmissions from nearly half of the surface of the earth. Telecommunications satellites in high LEO or in GEO can receive signals from a ground transmitter and relay it to a receiver distant thousands of kilometres from the transmitter.

Optical Imagery

For good quality photography (and observation from several other types of sensors) the best viewing angles are in a "nadir" cone centred on the vertical, directly below the sensor, while observations attempted at low (near-grazing) angles will be obscured by atmospheric absorption and scattering, and by screening of targets by intervening higher

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[4] Low Earth Orbits (LEO) are above the dense atmosphere (at about 150 km altitude), but below the Van Allen radiation belts (which begin at about 5000 km). Most satellites in LEO have altitudes between 200 and 1500 km, and periods between 1½ and 2 hours. Geosynchronous Earth Orbit is at 35,800 km altitude above the surface of the earth, and has a period of 24 hours. An important special case of geosynchronous orbit is the geostationary orbit (GEO), which circles above the equator with an orbital inclination of 0°, so that the satellite appears to be motionless when observed from the surface of the earth (and vice versa).

[5] See Figures I to III in the Annex for illustrations of the extent to which the field of view expands as the sensor moves to higher altitudes.

objects. For an aircraft, and satellites in LEO and GEO respectively, the radii of the circular areas on the earth's surface inside the cone where electro-optical surveillance will be good[6] are of the order of 10, 100, and 3000 km, with the corresponding areas roughly 500, 50,000, and 30,000,000 square km. These are very large differences, and it is evident that altitude confers a huge advantage in the field of view.[7]

However, as the altitude increases the resolution (or degree of detail that can be distinguished in the images recorded by the instruments) becomes poorer, and the distance between sensor and target may exceed the practical limits of detection.[8] For example, a camera in an aircraft flying at an altitude of 20 km would have resolution ten times as good as if the same camera were at an altitude of 200 km. And from geosynchronous altitude the sensors can "see" large objects, such as cloud formations, over a large proportion of the earth's surface, but they will not be able to distinguish objects a hundred times as large as those that can be resolved from from LEO.

Radar Imagery of the Ground and Sea Surface

Airborne radar has been used for many years as a navigation (and blind bombing) aid, able to produce rather crude images of large well-defined shapes such as coastlines or cities, and has served for the detection of ships, which stand out in contrast to the sea surface. The practical limits to the sizes of antennas that could be mounted on aircraft prevented high resolution. Improvements came with Sideways-Looking Airborne Radar (SLAR), and especially with Synthetic Aperture Radar (SAR), made possible with

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[6] The word "electro-optical" includes conventional photography and optical instruments such as telescopes, but also covers electromagnetic wavelengths in the infrared and ultraviolet bands. Furthermore it also refers to methods (such as television) of transmitting optical images from remote sensors, and for displaying them (such as is done on a cathode ray screen).

[7] See Figures II and III.

[8] The limitation of sensor range is particularly severe for an "active" system such as radar, which requires energy to traverse the path from the sensor's transmitter to the target and then back to the sensor again. It is less severe for a "passive" sensor, which relies on sunlight, or heat or electromagnetic energy generated by the target. A sensitive receiver can detect a transmitted signal at interplanetary distances, and the human eye can see stars at astronomical distances.

the extraordinary advances in computing and signal processing techniques. SLAR permitted an aircraft to map territory in a strip extending to a considerable range to one side of its track, with excellent resolution in the cross-track dimension. Synthetic Aperture Radar overcame the need for a large antenna, and produced excellent resolution in two dimensions and at all ranges.

The ranges from the high altitudes of satellite orbits make detection of small targets by conventional radar difficult, especially over the land, because of the very strong competing echoes from objects much larger than the desired targets. It has been possible to achieve detection of surface ships at sea, but in the case of the Soviet Radar Ocean Reconnaissance Satellites (RORSAT) it was necessary to use a nuclear reactor to provide sufficient power for the radar.

With the development of SAR, useful radar imagery from the much greater altitudes of LEO has become possible. With present technology it is likely that only a portion of the huge field of view from satellite altitudes will be used for collection of SAR imagery, but the ranges are likely to extend over hundreds of kilometres, and will be swept by a satellite in LEO at a speed roughly thirty times as fast as can be covered from an aircraft.

With present technology, useful radar imagery is not possible from the extreme altitudes of GEO.

Radar Detection and Tracking of Aircraft

Since its inception, the primary use of radar has been to detect and track aircraft in flight. For the first few years the radars were on the ground, seeking to detect aircraft against the background of empty space. The limits to the attainable range were set by the power of the transmitter, the size of the antenna, and the size of the target. With ground-based radar it was possible to increase the first two of these, whereupon the limit to range became the geometrical field of view, determined by the horizon as seen from the radar's antenna. In order to be detected, an approaching aircraft had to come above the horizon, as well as being within the maximum range determined by the design of the radar equipment.

If the radar is elevated, its horizon recedes to a longer range. Representative distances are 20 km from a ship, 200 km from a mountain overlooking the sea, 400 km from an aircraft at high altitude, and 2000 km from a satellite in LEO.[9] However, when the radar is at a high altitude, and attempting to detect aircraft below it against the background of the earth (or sea) instead of the empty sky, a new problem arises. The wanted target is so small in comparison to the background of unwanted reflections from the earth that its weak signal will be overwhelmed and be undetectable.

To overcome this, a signal processing technique is used which detects targets by their motion rather than the magnitude or their echo. Quite small targets can be detected if they are moving in a direction towards or away from the radar at a rate different from that of the background. It is this technique to permit Airborne Moving Target Indication (AMTI) that has made AWACS early warning and control aircraft, and also interceptors and air-to-air missiles, able to track targets flying at low altitude. The method works well at long range, but not in the cone beneath the radar, or when the targets are flying on certain courses. In addition to the ability of AWACS to track aircraft at low altitude, it should be noted that the American JSTARS aircraft were used in the Persian Gulf to detect and track moving vehicles on the ground and SCUD missiles in flight.

It would be a natural extension to apply to surveillance satellites the AMTI technique for detection of small moving targets against the background of the earth.

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[9] See Figure I.

However, the ranges are much longer.[10] To detect small targets it will be necessary to have large transmitter power and a large antenna on the satellite, or else to employ synthetic aperture techniques. The ideal solution would appear to be a combination of AMTI with SAR, which should be possible in principle, but no such development has been reported in the unclassified literature.

The type of radars discussed so far are classed as "primary radar," which transmits pulses of electromagnetic energy that cause echoes to be reflected from the body of the aircraft. This process does not require any cooperation on the part of the aircraft.

Two other systems for tracking aircraft are by "secondary radar" and by employing the Global Positioning System (GPS).[11] Secondary radar transmits an interrogation signal which causes a "transponder beacon" in the aircraft to respond (automatically) with a transmission of its own, which contains information regarding the identification of the aircraft. The other system (not yet in operation) which depends on GPS will compute the position of the aircraft from GPS signals, and, at arranged intervals, automatically transmit this via communication satellites to the air traffic control centres on the ground. Both of these methods require that the aircraft cooperate with the process by carrying an electronic device and keeping it functioning.

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[10] The zone in which aircraft may be detected begins at the outer edge of the nadir cone (inside which ground echoes will be extremely strong and the radial velocities used to discriminate moving targets small). The range to the edge of the nadir cone will exceed the altitude of the satellite, and beyond this most of the transmitted energy is scattered forward from the earth's surface rather than back towards the radar, and therefore produces less confusing background. See Figure II.

[11] The Global Positioning System (GPS, or "NAVSTAR") has a constellation (eventually to number twenty-four) of satellites in phased orbits around the earth at high altitudes, which allow several to be in line-of-sight, simultaneously, of any point on earth. The satellites transmit signals reporting their precise position at very accurately determined times. Quite a small receiver in an aircraft, ship, ground vehicle, or guided missile can combine the information to determine its exact location (including altitude as well as latitude and longitude). GPS demonstrated its usefulness in the Gulf War, and will soon be very widely distributed throughout armed forces and in civilian aircraft and ships. A similar Soviet system is called "GLONASS".

Movement of the Sensors and Targets

The rate at which territory can be surveyed from a moving elevated platform depends on the width of the path within the range of effective surveillance by whatever sensors are fitted, and on the speed with which the platform sweeps along this path. The distance to the horizon seen from a satellite is of the order of four times that seen from a high-altitude reconnaissance aircraft, although some sensors will not be able to exploit this to full range. The ratio of the distances to the limit for high grazing angles from satellite and aircraft is about ten. The satellite sweeps its path at a velocity generally around thirty times as fast as an aircraft. But for surveillance over a specified area of the earth, the aircraft is more efficient inasmuch as it can spend most of its airborne time over the area of interest, and can be diverted in order to pay particular attention to a selected target. In contrast, the satellite is over the area of interest for only a few minutes at a time, and for at most a few times per day, and can only make very marginal changes to its orbital path. But, on the other hand, the satellite is in orbit twenty-four hours a day, every day, which is far beyond the capacity of any one aircraft.[12]

Revisit Times

The requirements for surveillance of certain areas for certain purposes may vary from a minimum of one good image to a maximum of continuous coverage for an extended period. A map of a coastline may be useful for years. A map of a developing urban area or a silted estuary may need to be updated fairly frequently. A plot of the earth's geomagnetic field, of the state of the ozone layer, or of the concentration of acid rain should be updated more often than a terrain map. Imagery revealing unsatisfactory growth of crops will be wanted at short intervals, but only during a limited season. A map of ice cover may need to be remade within a few hours. And in cases of rapidly

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[12] Figure IV in the Annex shows the coverage of northern latitudes by a single satellite sweeping a path about 150 km wide for a period of twenty-four hours. It is clear that only a small fraction of Canadian territory is covered in a day.

developing emergencies such as hurricanes, floods, or forest fires, the changing situation will have to be monitored at short intervals.

When the targets of surveillance are moving themselves, revisit time becomes crucial. Ships do not move very fast, so that for surveillance of a fishing zone a revisit time of a few hours should be acceptable. But the probability of being able to associate a guilty ship with an oil slick decreases rapidly as the ship departs the scene of the pollution.

The importance of revisit time is greatest for surveillance of rapidly moving non-cooperating targets.[13] Aircraft could traverse the CADIZ[14] identification zone in less than an hour. If it is essential to track illegal entrants to their landing ground, a break in the track of half an hour could be fatal. However, a proportion of failures may be acceptable, as long as the probability of eventual success is high enough to provide a significant deterrent to repeated intentional violations. In the case of professional smugglers making repeated incursions, a satisfactory objective might be to catch them eventually, rather than every time. But if interception of an aircraft or a cruise missile is intended, and evasive action is taken, any break in tracking could spoil the interception.

For military purposes, revisit time need not be very short for the general collection of intelligence in a situation of relative calm, or for verification of arms control agreements. But for the monitoring of events in a time of crisis, or for conduct of actual operations of war, it will be highly desirable to have frequent updates. For reliable early warning of the launching of air or missile attacks, continuous surveillance would be required over the area of the expected flight of the attackers.

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[13] A sophisticated evader may be able to predict the times of satellite overflights, and time his movements to avoid detection or break tracking.

[14] The Canadian Air Defence Identification Zone (CADIZ) is over the oceans just adjacent to Canadian territory. Aircraft entering Canada from overseas are obliged to file flight plans before departure. When detected by radar, they are tracked through the CADIZ, and identified. The first means is by correlation with the flight plan, the second by radio communication, and if these fail, by sending up an interceptor aircraft for a visual identification.

Other Differences

International law establishes certain limitations on the freedom to deploy surveillance sensors. Ground-based sensors can only be emplaced with the permission of the sovereign power of the territory. Seaborne and airborne sensors are entitled to be in international waters and airspace. Satellites can be anywhere in space.

In an armed conflict, or when international law is disregarded, forces occupying foreign territory can erect mobile radars, ships can enter territorial waters, and aircraft can fly in hostile airspace. But these forms of trespass carry the risk of attack and destruction. Satellites are nearly invulnerable at present, although antisatellite (ASAT) weapons have been designed and there is no treaty to prevent their deployment.

Other than those of geometrical coverage, already described, the chief differences between the types of surveillance platforms are those of engineering, maintenance, and cost. A ground or ship-based system can be large, and easily provided with electrical power, maintenance personnel and facilities. An airborne system faces some limitations of size, weight, and power. Repair and maintenance of airborne equipment will probably be carried out in good facilities on the ground, between sorties. But once launched, a satellite can only have equipment failures corrected by switching of redundant components already designed into the system, or by a very expensive visit by a manned space vehicle. In terms of cost, a permanently manned radar station in a remote locality is expensive. A large reconnaissance aircraft together with the necessary ground facilities and personnel is very expensive. And a satellite is very expensive indeed.

VI THE MILITARY SIGNIFICANCE OF SPACE

Although long-range ballistic missiles rise high enough in their trajectories that they might be considered to be "space vehicles,"[15] the passage through space only lasts for a period of twenty to thirty minutes. The generally accepted definition of a "satellite" is that it completes at least one full orbit around the earth.[16] In this paper we do not include ballistic missiles in the category of "space vehicles."

Space has had great military significance since the launch of Sputnik in 1957. For the first few years the key role was for the collection of strategic intelligence regarding systems operated by the USA and the USSR.[17] Later it was used in support of strategic systems through such means as provision of precise navigation for SSBNs, measurement of accurate geodetic and gravimetric data for the guidance of ICBMs, and assembly of accurate ground contour maps for the guidance of cruise missiles.

The part played by satellites in the collection of intelligence has been enormous, and many of the benefits derived by the USA have been shared with her allies, including Canada. In times of international crisis the intelligence obtained from satellites can have crucial importance, as it can for tactical planning in time of war. The US has been able to help its allies during several crises, including the Falkland Islands and the Middle East. The Coalition forces in the Gulf War relied on satellite observations for many purposes, including planning of air strikes and land operations, and for bomb damage

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[15] An ICBM with a terrestrial range of 10,000 km rises to a maximum height of 1300 km above the surface of the earth, which is higher than the apogee of most satellites in Low Earth Orbit, but the missile completes its trajectory in about half an hour.

[16] The lowest circular orbit barely above the sensible atmosphere will take 88 minutes to complete one circumnavigation of the globe. Any higher orbit will take longer.

[17] Three very different types of sensor were important for this purpose. Photography revealed the existence and location of missile silos and airfields, infrared sensors detected the heat from rocket launches, and radio receivers collected telemetry signals emitted during missile tests.

assessment.[18] This paper concentrates on the use of surveillance satellites for defence against ballistic missiles and aircraft of intercontinental range, but it is becoming very evident that they will be assuming vital roles for many aspects of military operations at the tactical level as well.

Space has played an important part in the establishment and maintenance of stable strategic nuclear deterrence. A vital role was the provision of reliable early warning of the approach of ballistic missiles towards the sites of the retaliatory weapons based in the United States. The most effective warning system consists of satellites in geosynchronous orbit carrying infrared sensors able to detect the heat from the rocket exhaust when a large ballistic missile (or space vehicle) is launched almost anywhere in the world.[19] During recent conflicts in the Middle East they detected the launching of ballistic missiles in Afghanistan and from Iraq. These spaceborne warning systems are supplemented by large ground-based radars located in Greenland, Britain, Alaska, and the coasts of the continental United States. Although ICBMs from the (former) USSR directed towards targets in the USA would pass over Canada, none of the warning installations are on Canadian territory.

Another contribution of space surveillance to crisis stability is made by detection of above-ground nuclear explosions. If, in a time of uncertainty and crisis, systems are in place which can be relied on to report the launching of missiles or the detonation of nuclear explosions anywhere in the world, and they indicate that neither has in fact occurred, then miscalculations that might motivate a decision to launch a nuclear attack are less likely to be made.

Some other services provided from space, such as weather forecasts and navigation aids, are made generally available to all allies (and often to neutrals and even to

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[18] See *Space Support to Operation Desert Storm: A NORAD Perspective*, by LGen R.W.Morton. Royal Canadian Military Institute 1991 Yearbook Toronto, 1992, pp. 6-10. Some imagery was purchased from commercial sources, probably used for general intelligence obtainable at less than the highest possible resolution.

[19] Usually labelled "DSP" (Defense Support Program).

enemies). Great reliance is placed on communications relayed via satellite, and it is often possible for defence organizations to lease services from commercial sources to supplement their own dedicated military circuits.

The small scale of the operations of the Canadian forces, and the services made available by the United States government, through NATO, and from international commercial sources, have made Canadian investment in space for military purposes unnecessary in the past, other than for partial fulfilment of the needs for long-distance communications. The lack of Canadian-owned space capabilities could be a handicap for some security operations inside Canada, or carried out abroad without the support of better-endowed allies, but no such problem has arisen in the past.

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VII SPACE AND BALLISTIC MISSILE DEFENCE

Defence Against Intercontinental Attack by Ballistic Missiles

The only practical countermeasure to the threat posed by ICBMs and SLBMs has been the strategy of deterrence, requiring possession of an assured capability to retaliate for an attack. Various space projects have made important contributions to deterrence. The stability of the system was increased by providing reliable warning of attack. The effectiveness of the potential retaliation was increased by improving the accuracy of the missiles. We should never forget that the strategy of strategic deterrence has been completely successful, in spite of the predictions by its strident critics that it would lead to global destruction.

Although obliged to depend on deterrence, the possibility of active defence that would be able to intercept and destroy ballistic missiles in flight has attracted attention and extensive research and development programmes for almost as long as ICBMs and SLBMs have existed. At first the approach was to use ground-based interceptor missiles armed with nuclear warheads.[20] Systems were built and deployed, but the severe limitations agreed by the two superpowers in the bilateral ABM Treaty of 1972 have been observed. Nevertheless the R&D continued, and was expanded by the American Strategic Defense Initiative (SDI) instituted by President Reagan in 1983. New capabilities in sensing, computing, guidance, and projection of directed energy offer several potential methods of destroying ballistic missiles in flight.

The initial focus of the SDI programme was to defend against a massive attack by hundreds of Soviet ICBMs and SLBMs projecting thousands of warheads and decoys against the United States within a time span of a few minutes. The only possibility of

[20] The first opponents of BMD questioned the feasibility of "hitting a bullet with a bullet". The supporters decided to annihilate the bullet in a nuclear explosion. But with today's technology it is proving possible to put small inert objects in the path of the bullet which will exploit its own enormous velocity to destroy it in a high speed collision, using kinetic energy rather than nuclear energy.

preventing most (or hopefully nearly all) of the warheads from striking their intended targets was to provide a "layered defence" with different types of defensive weapons intercepting different phases of the missile trajectories.

The stages thought to offer the best opportunity to decimate the attack were the first two, the boost phase (during which the propulsion rockets were burning and the missile accelerating) and the post-boost phase (while the multiple warheads were being projected into their independent trajectories and the decoys dispersed). Both phases would be completed within ten minutes of liftoff, and within a few hundred kilometres of the launch site, far from territory on which ABM equipment could be sited. The only way to intercept a missile in either of these phases would be with a weapon based in space, and directed by information obtained by sensors based in space.

The other two stages in the flight of an ICBM or SLBM are the mid-course and the terminal phases. The mid-course phase lasts the longest of the four (twenty to thirty minutes) and covers a long distance at high altitudes. It is not clear at the present time whether sensors, and weapons capable of destroying the warheads in mid-course (in spite of the decoys) would best be based in space, on the ground, or even possibly in aircraft or on ships. The terminal phase comes when the warheads reenter the atmosphere and descend to their points of intended detonation. It seems probable that sensors and weapons for terminal defence would be based on the ground or in aircraft, and would only be able to prevent impact on intended targets located fairly close to the position of the defensive weapons.

If such a layered system were to be deployed for the defence of the United States against ICBM attack from the direction of the (former) USSR, Canadian territory would have little significance for interceptions in the boost or post-boost phases, which would have to be conducted from satellites already in orbit. If ground-based, airborne, or sea-based sensors or weapons were needed for mid-course interceptions, many of these would probably have to be located in Arctic regions, and Canadian territory could be well-placed for such sitings. In the case of terminal-phase defence, much would depend

Most of the Iraqi SCUD ballistic missiles directed against Saudi Arabia and Israel in the Gulf War were fired from mobile launchers. The rocket exhaust was detected by the American missile warning satellites in geosynchronous orbit. The moving missiles in flight, and soon after this the launching vehicle leaving the site, were detected by JSTARS aircraft, thus providing warning and tracking information for the defensive Patriot batteries and also for tactical aircraft on patrol for the attack of SCUD launchers. The success of the ground-based Patriot system (which had been designed for defence against aircraft) indicates the potential usefulness of ground based ATBM weapons, as well as their probable dependence on airborne and space-based sensors.[26]

The relevance of all of this to Canadian defence is that there is likely to be less priority given by the United States to defence of North American territory against intercontinental ballistic missiles, and such research, development, and possible deployment as does occur will probably be concentrated on terminal defence located on the ground (and possibly airborne) in the vicinity of the targets to be defended.

However, as Tactical Ballistic Missiles (TBMs) proliferate, Canadian Forces deployed abroad could well find themselves under attack by TBMs, quite possibly armed with nuclear, chemical, or biological warheads. In these circumstances they would no doubt appreciate the presence of an effective ATBM defence.

This change in the strategic situation and in the nature of the SDI programme suggest that the decision of the Canadian government to decline the invitation issued by the USA in 1983 to participate in SDI should be reviewed. There is little in the GPALS programme to create concern over destabilization or aggression, and much to recommend

[26] Post-war analyses of the performance of Patriot are critical because damage was done to buildings by warheads and debris of SCUD missiles, and also by some of the defending Patriot missiles. See "Lessons of the Gulf War Experience with Patriot", by Theodore A. Postol, *International Security*, Winter 1991/92, pp.119-171. But the lesson which encourages proponents of ATBM defence is that it was possible to hit and damage most of the SCUDs in mid-flight, and this in spite of the fact that Patriot had been designed to intercept aircraft, which are much more vulnerable, and would be approaching at less than one-sixth of the speed of a SCUD.

the acquisition of a system capable of defence against tactical ballistic missiles in distant theatres. Participation in the research and development would improve Canadian access to high technology, and also the understanding needed for competent assessment of possible future plans to acquire or deploy new systems, including those contributing to surveillance from space.

For those concerned about a possibility of being drawn into some project in which Canada did not wish to participate, it should be clear that decisions regarding significant participation come at the stages of procurement, deployment, and agreement over the functions of direction and control of an operating system. Research and development are necessary in order to discover what could be done and how much it would cost, and not to determine what will be done, by whom, or at whose expense.

To make informed decisions on the latter matters requires full understanding of the technical capabilities of new devices, and the way to acquire this understanding is to participate in the research and development.

VIII SPACE AND AIR DEFENCE

Active Air Defence of North America

Through the 1950s the capability to deliver a nuclear attack at intercontinental range depended exclusively on heavy bomber aircraft. In the 1960s ICBMs and SLBMs were added, forming the "triad" of strategic nuclear weapons.

Unlike the problems posed by ballistic missiles, a degree of active defence against bomber aircraft has always been possible, although never able to achieve the near-perfect effectiveness that would be needed if cities were to be protected from mass nuclear attack. The methods of air defence developed during World War II depended on ground-based radar, antiaircraft guns, and radar-equipped interceptor aircraft armed with machine guns and cannon. Post-war improvements saw the interceptor aircraft with guided air-to-air missiles, and the heavy ground-based antiaircraft guns replaced by surface-to-air guided missiles.

For air defence of a large area, a severe limitation of ground-based radar is its inability to see over its local horizon.[27] This offers attacking bombers the opportunity to penetrate the defences by flying low and between the radar stations and gun and missile batteries. The time during which ground-based guns and missiles designed for low-altitude air defence can engage fast-moving targets is very brief, and the area covered from any one site very limited. An interceptor aircraft flying at medium altitude can maintain line-of-sight to a low-flying bomber, but visual detection and tracking is difficult by day and virtually impossible in the dark, and radar detection is hindered by the enormous volume of competing reflections from the surface of the earth.

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[27] The horizon described earlier, and the numbers in the table of the Annex, assume a smooth earth (as is encountered at sea). The presence of hills or buildings adds higher obstructions, the effects of which need to be taken into account in calculating the coverage possible from any specific ground site against low-flying aircraft.

Canada's geographic position gave her territory major significance for the preservation of deterrence, and the active defence of North America against bomber attack. As was the case later on for ICBMs, the direct routes between bases in the Soviet Union and likely targets in North America led over the Arctic and northern and central Canada. Defence of the continent posed two main requirements: early warning to alert the defences, and active defences to intercept the bombers before they reached their targets in southern Canada and throughout the United States. The total area of the two countries was too great to allow consideration of the installation of a network of ground radars able to provide complete cover against bombers at high altitude, and nearly complete coverage at low altitude would have been impractically expensive for more than a few small selected zones.

What was done was to install two lines for early warning and a central zone for tracking and interception. The Distant Early Warning Line (DEW Line) extended one strip of ground-based radar cover from Alaska across the north of Canada to Greenland, and the Mid-Canada Line another across Canada from British Columbia to Labrador, at a latitude of about 55° North.[28] Across southern Canada and down the Atlantic and Pacific coasts of Canada and the United States a multi-layered ring of ground-based radars provided solid cover against bombers at high altitude, and control for interceptor aircraft based on the ring.[29] Inside the ring there were further zones covered by ground-based radar and interceptor aircraft. Heavy antiaircraft guns and surface-to-air missiles were also deployed in the United States, but progressively withdrawn in later years.

As the threat from ballistic missiles overtook that from bombers, and no serious level of active ABM defence was mounted, the active air defences were gradually reduced to a very low level. But early warning and identification was strengthened by modernization of the DEW Line, placing improved minimally-manned radars along the

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[28] The Mid-Canada Line was able to detect aircraft at any altitude. It used the Doppler principle to signal the presence of moving objects. It served as a trip-wire, but could not track targets. The line was deactivated in 1964.

[29] The multiple line of radars across southern Canada was known as the "CADIN Pinetree Line".

same general line as before, together with Forward Operating Locations serving as bases for interceptor aircraft. This system is now known as the North Warning System.

Detection of Aircraft at Low Altitude

It has been explained that the coverage by ground-based radar of vast uninhabited areas against high-altitude aircraft would be extremely expensive, and against low-altitude aircraft continuous cover over a large hilly area effectively impossible.[30] To achieve continuous tracking of low-flying aircraft, the sensors must be at high altitude, but nevertheless able to detect their targets against the much stronger background of the earth.

As described earlier, this can now be done with AWACS, using the technique of AMTI. The American AWACS also has the communications and display facilities to allow controllers to direct interceptor aircraft towards targets. Modern interceptor fighters are also equipped with a form of AMTI.

AWACS has demonstrated great value for tactical air warfare, and shows to best advantage in a theatre of limited area such as Central Europe or Iraq. For air defence of North America, the range of the AWACS radar (about 400 km against low-flying targets) allows one aircraft to cover no more than a rather small proportion of the continent, and that only for a few hours at a time. The high cost of an AWACS precludes any approximation to continuous coverage of an entire continent. It is natural to look to space for the eventual solution.

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[30] In the mid-1980s the USSR was thought to have 10,000 ground-based radars deployed for air defence of its home territory. This should have produced good cover over nearly all of the USSR against large (non-stealthy) aircraft at medium to high altitude.

Space-Based Radar for the Detection of Aircraft

So far, air defence has received little assistance from space. As has been discussed already, extension into space of the very satisfactory performance of AWACS presents several serious technical difficulties, which must be overcome before aircraft can be detected by active radar from satellites.[31] It seems obvious that the first workable solutions are going to be for LEO altitudes, and that continuous coverage of a huge area for the detection of non-cooperating aircraft by one satellite in GEO cannot be contemplated in the foreseeable future.

A satellite in a Low Earth Orbit will pass over any small area of interest in a few minutes, and will not return for a time measured in hours or even days.[32] More nearly continuous cover can only be achieved by having successive overflights by a properly synchronized constellation, populated by a considerable number of satellites.[33] However it is probable that a certain degree of intermittency would have to be accepted, and could be tolerable for the tracking of a target once it had been detected.

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[31] Unless it is powered by a nuclear reactor, a satellite will probably not be able to transmit signals as strong as those of AWACS. To strike the earth at a low glancing angle, so that the reflections returning back from the ground are not too strong, and so that moving targets can have a high radial velocity, the range will need to be at least 250 km. To have a good resolving power at long range without a large antenna, it will be necessary to employ the SAR technique, but to detect small moving targets against a large background the techniques of SAR need to be combined with those of AMTI.

[32] The revisit time depends on the latitude of the area of interest, the period and inclination of the satellite's orbit, and the width of the swath which it can survey. To give an example, a swath 500 km across, being swept by a satellite in a circular orbit with an inclination of 75° and a period of 91 minutes (corresponding to an altitude of 325 km) would cross over a point on the Arctic Circle on an average of once every 19 hours. But the same swath would cross a point at the most southerly latitude of Canada only once in every forty hours. And for both cases the satellite would be moving along at a rate of 500 km in about one minute.

[33] The number of satellites required to produce continuous cover at a given latitude depends on the design of the system, in particular on the swath width, the orbital period, and the inclination. It is likely that it would require approximately a dozen satellites to provide nearly continuous cover of a zone at a high latitude, but that even then there would be "blind spots" for certain combinations of position, velocity and courses of the target aircraft.

As is the case for many other types of satellite services, a system put into operation for the surveillance of any particular area will automatically exercise some degree of surveillance over most of the rest of the entire world. Another factor to be considered is that the benefits of worldwide tracking of aircraft (including those not prepared to cooperate in their tracking) are likely to be of benefit to a host of government and civilian responsibilities beyond those related to defence. The enormous cost of a large constellation of sophisticated satellites, combined with the global coverage which they would make possible, suggest that Space-Based Radar for the tracking of aircraft may be an enterprise to be undertaken on an international scale for services of many kinds. But before this is feasible it will be necessary to develop a satisfactory spaceborne MTI that can be combined with a synthetic aperture antenna.

This discussion has focused on space-based detection of aircraft using active radar as the sensor. Another type of detection which has been investigated for the purpose of tracking aircraft is by infrared sensors, which are able to detect the heat from aircraft engines. This method can be used to detect ships as well as aircraft, and possibly also cruise missiles, but will not function through clouds or rain.

The reductions negotiated under START tend to increase the relative presence of bomber aircraft in the (considerably diminished) total number of strategic weapons, and also encourage the loading of bombers with Air-Launched Cruise Missiles. The air-breathing threat will become more difficult to deal with as stealth technology reduces the radar signatures of both aircraft and cruise missiles. Nevertheless, under the changed circumstances of the 1990s, it seems probable that far less priority will be placed on defence of North America against intercontinental nuclear attack. *There would not appear to be a strong case at present to invest large sums of Canadian money in acquisition of space-based radar if its sole purpose is to be for air defence. But it could also serve several other important purposes as well, and decisions ought to be taken considering all of these.*

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IX ARMS CONTROL, DISARMAMENT, PEACEKEEPING, AND SPACE

It is most unlikely that the important bilateral SALT agreements concluded during the Cold War could have been reached had it not been for the ability of surveillance satellites operated by the two superpowers to verify compliance by the other party with the undertakings. Subsequent agreements (the bilateral INF and START and the multilateral CFE) have included other much more cooperative and intrusive provisions for verification. But the effectiveness of some of the procedures such as on-site inspections is likely to depend to a considerable extent on intelligence obtained from satellites, drawing attention to areas or activities which warrant closer inspection than can be conducted from space. Moreover, circumstances could arise in the future in which cooperation deteriorated, and intrusive inspections were obstructed or denied.

A tendency in recent years, which is likely to accelerate in the future, is for important arms control and disarmament negotiations to be multilateral rather than bilateral, and to involve conventional as well as nuclear, chemical, or biological weapons. If the demand for adequate and effective verification also continues, the parties will wish to take advantage of satellite surveillance to support this verification. It is likely that the USA, and possibly whatever state succeeds to the space facilities accumulated by the former Soviet Union will make some of their observations available to the other parties. But there will be an increasing desire by all members of multilateral agreements to have full access to satisfactory means of verification, even if they do not possess the highest capabilities of the systems of the superpower(s).

In this regard, France has recommended the creation of an International Satellite Monitoring Agency (ISMA)[34], which the USSR followed with a variant having the title International Space Monitoring Agency, and also proposed an International Space

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[34] See *Prevention of an Arms Race in Outer Space: A Guide to the Discussion in the Conference on Disarmament*, by Pericles Alves. UNIDIR, United Nations, New York, 1991, pp.118-120 and 154-159. See also "Commercial Observation Satellites and Verification", by Bhupendra Jasani. Chapter 14 in *Commercial Observation Satellites and International Security,* (eds) Krepon, Zimmerman, Spector & Umberger, SIPRI, St. Martin's Press, New York, 1990, pp.154-159.

Inspectorate, which would conduct on-site inspections prior to the launching of space vehicles[35]. Canada has proposed that specially designed surveillance satellites be launched for the purpose of verifying multilateral arms control treaties. Two versions of this plan were studied. PAXSAT A would use space-to-space inspection to monitor the presence of weapons in satellites (as might be there for the purposes of ABM or ASAT, for example), while PAXSAT B would have space-to-ground sensors to observe conventional weaponry subject to arms control agreements (for example CFE).[36]

For many of the objects of interest for the verification of conventional arms control agreements, the resolution of existing commercial surveillance satellites would be unsatisfactory. But if low-resolution images caused suspicion of non-compliant activity, it is possible that further investigation could be arranged using aerial observation or on-site inspection. And resolution is being improved with successive generations of civilian surveillance satellites, together with expanding capability to collect images over a wide spectrum of wavelengths which reveal far more than can be seen in the visual band alone.

Peacekeeping has been a multilateral activity from the beginning. Naturally enough, the hostile factions between whom peace is being kept are likely to be unforthcoming regarding their deployments and weapons, and may not permit overflights by aircraft of the territory which they control. The United Nations has resisted the formation of a permanent military staff which might accumulate information regarding parts of the world in which peacekeeping might be required. There have been occasions in which the peacekeeping forces were handicapped by lack of accurate and up-to-date maps of the area in which they were operating.

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[35] Alves, *ibid*, pp.121-124.

[36] Alves, *ibid*, pp. 125-128, and *PAXSAT Concept: The Application of Space-Based Remote Sensing for Arms Control Verification*, External Affairs Canada, Verification Brochures No. 2, 1987.

While the needs of peacekeeping might not warrant the expense of a dedicated satellite, any surveillance satellite capable of producing a good map could prove very useful, while a satellite able to collect high-resolution imagery of selected areas (as would be necessary for verification) could be more valuable still, especially so if it were possible for an international peacekeeping organization to order imagery of a specified area to be taken with a minimum of delay.[37]

With its record of support for the United Nations and internationalism, and of constructive initiatives in both peacekeeping and verification, as well as for its expertise in the techniques of remote sensing, Canada should take a prominent role in the planning of a multinational organization for the use of space surveillance in support of arms control, disarmament, and peacekeeping.

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[37] See *Overhead Imaging for Verification and Peacekeeping: Three Studies*, by Allen V Banner. Arms Control Verification Occasional Paper No. 6, External Affairs & International Trade Canada, Ottawa, 1991.

[illegible] space [illegible] launched [illegible] this plan [illegible] presence [illegible] of ASAT, for example, [illegible] conventional weapons [illegible] (for example GPS).[34]

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[35] Alves, *ibid*, pp.121-124.

[34] [illegible] pp.115-128, and [illegible] Canada: The [illegible] of [illegible] Space [illegible] No. 2, 1987.

X PEACETIME REQUIREMENTS FOR CONTROL OVER NON-COOPERATING PARTIES

While many activities in a generally law-abiding country require some degree of government control, this control usually also depends on, and obtains, cooperation on the part of most of the citizens. An example is motor vehicle traffic, regulated by laws, signs, and traffic signals which are usually obeyed by nearly all of the motorists. But it is necessary to apprehend and discipline those who do not obey, or at least enough of them to deter more widespread non-compliance.

Non-cooperating behaviour on the part of foreigners can be similar to that of Canadian citizens, involving transgressions against Canadian laws whose validity is not being challenged. But if a foreign state does not accept the validity of Canadian laws, and wilfully transgresses, this becomes a challenge to Canadian sovereignty. The ultimate stage of non-cooperation is an act of war.

The boundary between law enforcement and protection of sovereignty is difficult to define, and in this paper we will not attempt to make the distinction or to identify which agencies should be responsible for which activities. It is, however, clear that the upholding of both national laws and national sovereignty are important responsibilities of the national government. The Department of National Defence has the primary responsibility for dealing with acts of war, and may be called upon to aid other departments for law enforcement or maintenance of sovereignty.

The present and potential contributions of space surveillance to the defence of North America and of possible overseas commitments of the Canadian Armed Forces have been described already. Surveillance from space can serve to support control over many types of non-cooperation that fall short of a military threat, but nevertheless require counteraction by the national government. Economy dictates that if an expensive space surveillance system, capable of effective use against non-cooperating parties that offer a military threat to national security, can also be used to aid in the solution of other national problems, then it should be employed for all of these purposes. Likewise, if the capabilities for military defence that are provided by the Armed Forces can be employed for useful contributions to national sovereignty or security in peacetime, without detracting seriously from their effectiveness for the more traditional roles of defence, then they should be employed for all of these purposes.

Decisions regarding the allocation of government resources for the discharge of major national responsibilities should be taken on a national basis, not on the basis of separate budgets restricted by piecemeal mandates of departmental responsibility.

In times of peace, most of the tasks of control over non-cooperating persons, groups, or organizations fall to the police, law courts, and prisons. The control and policing of automobile traffic is aided by overhead surveillance from helicopters above city traffic (more to observe congestion than to prevent violation), and from light aircraft over highways (which can produce convictions for speeding), but there does not appear to be an immediate potential for support of ground traffic control from space.

Control of air traffic is carried out by regulations, communications, and surveillance by ground radars. Nearly all aircraft cooperate, since their own safety is at stake, as well as continuation of their licence to operate. However, while some non-cooperating aircraft may pose a hazard to safety, including safety of other aircraft, and others may use light aircraft in the course of breaking laws regarding sport fishing, for example, problems of a different nature arise because of the ease with which aircraft can cross international borders.

The opportunities to exploit the capabilities of space surveillance to improve the functioning of customs, immigration, and narcotics control would seem to rest with the detection and tracking of aircraft crossing the border, and ships or boats approaching the coast, and to do this in a manner not depending on cooperation by the target vehicles (in fact, better without their knowledge). It would also be desirable to be able to observe these same vehicles after they had reached their destinations and stopped moving, or when ships stopped at sea, or moved very slowly, perhaps to transfer illegitimate cargo. Resolution adequate to obtain a description, or better still to perform individual identification of stationary or moving targets would be very useful.

A difficulty faced in these operations will be the large background of legitimate cooperating traffic amongst which a small number of non-cooperating targets must be detected and discriminated. In this regard, assistance should be forthcoming from the planned control of civil air traffic by continuous automatic reporting of their positions using GPS equipment and satellite communications. Either the air traffic control system or the customs and immigration system would need to track a target which behaved in a cooperative manner but then landed at an unauthorized place after crossing the border. The customs and immigration system would also have to be able to track a target which was not making the reports.

The technical demands of being able to detect and track fast moving, slow moving, and stationary vehicles, and to provide resolution adequate for individual identification, may be too diverse to be met by one type of satellite. But a satellite capable of meeting any of these demands should be able to serve the needs of several users, for the responsibilities of law enforcement, security, and defence.

Another task of law enforcement for which space surveillance should be able to provide important information is the protection of off-shore fisheries from illegal exploitation, whether by Canadians or foreigners. Here the targets are fair-sized vessels which may be stationary or moving very slowly, and which may be obliged to show large markings suitable for easy identification from a low-flying aircraft. One would want the satellite to be able to establish the course, speed, and position of the vessel and to determine whether it was actively fishing. Actual identification would probably require a close approach by an aircraft or ship, and determination of a fishing violation might be possible only after boarding by properly authorized inspectors.

With its geographical significance for the aerospace defence of North America, its huge lightly populated area, and widely dispersed natural resources, Canada is open to a number of challenges from non-cooperating parties, and could obtain important assistance from space.

XI MONITORING OF THE ENVIRONMENT AND OF NATURAL DISASTERS

Whether caused by man or nature, deterioration of the global environment is a threat to be taken very seriously in the next few decades. Where the deterioration is clearly due to increasing population and to avoidable practices, it is likely to become a major cause of international friction, especially after international agreements have been reached to limit or reduce environmentally damaging activities, such as generation of atmospheric pollutants, including acid rain, or pollution of international waters, or those of neighbouring states.

Monitoring of the world's atmosphere and oceans will be a monumental task, probably impossible by any means other than satellite surveillance.

Environmental protection takes many forms. One which involves non-cooperating human activity and could make use of space is the detection of pollution, and if possible the establishment of its source. Sensors such as multispectral scanners, scanning lidars, and radiometers are able to detect small concentrations of many substances in the atmosphere or on water surfaces. Depending on the ability of the sensors to produce imagery, it should be possible to detect the existence, size, and nature of oil slicks on the water, and of some industrial effluent on or in the water, or in the air, and in some cases to establish the place from which these originated. More difficult, but desirable, would be tracking and identification of ships responsible for water pollution. Some sensors would also be useful for monitoring environmental conditions such as the generation of smog in cities or deterioration of vegetation.

The category of disasters caused by nature, rather than man, includes hurricanes, typhoons, tidal waves, earthquakes, volcanic eruptions, floods, droughts, and forest fires. Forecasting of disastrous hurricanes or typhoons are extreme examples of meteorological prediction, and these are becoming increasingly dependent on satellite observations. In areas where such disasters recur, warning can be used to take precautions capable of saving lives and property. There are other calamities, such as floods, droughts, and forest fires which can sometimes be predicted. Moreover, for these and other emergencies which cannot be forecast, such as volcanic eruptions or earthquakes, the development and effects can be monitored from space, enabling evacuation, countermeasures, and rebuilding to be undertaken.

There are some long term threats to health and economic prosperity which may, if the most pessimistic predictions prove to be accurate, produce natural calamities creating gradual rather than sudden harm. Examples are depletion of the ozone layer, spreading of acid rain, and effects of climatic change such as global warming and the rise of the sea level. The understanding of these processes will depend on collection of masses of data on a global scale over a protracted period of time. The ideal means of collecting much of this data is by appropriate sensors in satellites. This is the type of undertaking clearly requiring international participation, in which the large area of Canada and its northern latitudes make us an important partner. A large programme known as "Earth Observing System" is being planned by NASA, to measure global changes in many measurable characteristics.

XII THE MANY OTHER POTENTIAL BENEFITS OF SPACE SURVEILLANCE

Four of the most important services made available to civilian users by satellites are communications, weather forecasting, navigation, and assembly of accurate maps and charts. These have been discussed already because of their parallel application for defence. The requirements for military use are somewhat more demanding. It may be more important to forecast visibility from different altitudes in the atmosphere, fixing of positions may need to be more accurate than needed for safe navigation, and geographical information may need to be very precise, and include data regarding topography, depth of water off beaches and estuaries, thickness of ice, and precise gravity. The sensors and communications with the ground should be resistant to jamming, and possibly to physical attack, and may need to be duplicated by back-up units able to replace any that are destroyed.

The use of space to provide these and other services is so new, and the mass of data being collected is so great, that one of the most important applications is for scientific research to increase understanding of the many relevant phenomena, and to develop the technology that will lead to better services in the future. For example, the various satellites used for weather forecasting measure such things as cloud movements, temperature and water content of the air, presence of aerosols in the atmosphere at different altitudes; currents, temperatures and wave heights of the sea surface; and extent of snow cover of the land and ice cover of water.

Collection of imagery of the land at various wavelengths produces information regarding the growth and health of crops and forests, including determination of areas cut, and also of the formation and chemical composition of rocks and soil, the latter being useful for location of mineral deposits. Urban planning can benefit from up-to-date images showing recent growth of cities. Lasers can measure the depth of shallow waters, and also produce detectable reactions from chemicals polluting the surface.

There is probably no country in the world better suited than Canada to benefit from the services of the types just described.

XIII CONCLUSIONS AND RECOMMENDATIONS

1. Spaceborne surveillance will be important to Canada for a wide variety of applications, which include surveillance of non-cooperating targets of several kinds (non-military as well as foreign military), verification of arms control agreements, environmental monitoring, management of resources, mitigation of natural disasters, and acquisition of scientific information.

2. Canada has had admirable success in space communications and scientific research, and also in the mastery of the techniques of data processing from remote sensing, from both space and aircraft platforms. This forms a promising basis for progress in further ventures in the realm of space surveillance.

3. In the defence and security plans of the United States and its allies, the roles of space surveillance are likely to be directed less than in the past towards defence against large-scale intercontinental attack, and more towards defence against tactical ballistic missiles in distant theatres, support of conventional military operations, including peacekeeping, and the verification of arms control agreements.

4. Defence and law enforcement must deal with fast-moving non-cooperating targets, which pose the most difficult and expensive problems for surveillance from space. The least demanding type of space surveillance is over stationary objects which do not require repeated observation.

5. For civilian applications, the roles of space surveillance are likely to be directed towards environmental monitoring, support of offshore security, management of natural resources, and mitigation of the effects of natural disasters.

6. A crucial and growing problem of space surveillance is the timely and efficient processing and distribution of the vast volume of data. Demonstrated expertise in

this area should put Canada in a good position to be a significant international contributor.

7. Space surveillance systems procured for defence, and operated by the Canadian Armed Forces, will be capable of valuable services for many other functions of national importance.

8. In order for the opportunities to be realized in Canada, there is urgency for good cooperation among departments and agencies of government, and with industry.

9. There is opportunity for international cooperation in the design, procurement, and operation of spaceborne surveillance systems.

Recommendations

The Canadian government should declare space surveillance to be a key strategic technology, to be developed for the benefit of Canadian prosperity, security, and industrial competence.

Research, development, and acquisition of space surveillance systems should be planned so that the maximum benefits can be obtained from the eventual working systems by a large number of users.

Defence and security should not be segmented from the many other services of national importance that can be provided from space. Serious planning should be undertaken for the employment in peacetime of the equipment and personnel of the Canadian Armed Forces in activities of national importance other than those of a strictly military nature, when these do not detract to a critical extent from their ability to provide defence when needed.

Cooperation should be obtained among government departments and agencies, and Canadian industry, to promote coordinated activities in a national programme for space surveillance.

Research and development should be accelerated for the following objectives:

1. The design of a spaceborne system able to detect and track non-cooperating moving targets, such as aircraft, surface ships, and cruise missiles;

2. Investigation of the possibility of combining the techniques of airborne moving target indication with synthetic aperture radar, so that one satellite can track moving targets and also (though not necessarily simultaneously) produce high-resolution images of stationary objects;

3. The design of improved spaceborne radar, electro-optical, and other sensors able to produce high-resolution imagery of the earth, and to detect low concentrations of chemical contaminants in the atmosphere and on water surfaces;

4. Development of overhead sensing techniques (both spaceborne and airborne) for verification of arms control agreements and for assistance to peacekeeping operations;

5. Design of data-handling techniques enabling a very large vlume of information to be collected in space and elsewhere, transmitted, processed, fused, filtered, and distributed, on a controlled and selected basis, to a large number of users equipped with interactive displays; and

6. The provision of low-cost high altitude airborne test platforms such as Remotely Piloted Vehicles or balloons.

For the design, procurement, and operation of the most expensive systems, requiring constellations of advanced satellites, partnership should be sought with the United States, and/or other international collaborators. The system design should be such, and the Canadian contribution sufficient, to permit Canada to employ its satellites for independent operation, should this ever be desired.

Canada should consider the possibility of participating in development of space-based sensors for the American Air Defence Initiative, and governmental participation in the important space-based surveillance aspects of the (now substantially revised) American SDI programme.

ANNEX: FIELDS OF VIEW FROM ELEVATED SENSORS

To begin with geometry, the dominant factor is the spherical shape of the earth. While a sensor on a ship has an unimpeded line of sight to half of the universe,[38] the half that is "below the horizon" includes nearly all of the surface of the earth and the atmosphere above it, which for many purposes of surveillance are the zones of maximum interest.

A radar mounted 25 metres above the sea on the superstructure of a ship has a geometrical line-of-sight which grazes the sea surface at a horizon distant 18 km away. The radar should be able to detect floating targets out to that range, and somewhat beyond if they have a superstructure extending well above the waterline.[39]

Against targets in the air, the maximum range permitted by the line-of-sight will be longer. An aircraft approaching the ship at the high altitude of 11.6 km (38,000 ft) will be below the geometric line-of-sight until it comes to a range of 400 km. Within that range the ability to detect and track the target (assumed to remain at the 11.6 km altitude) will depend on the design parameters of the radar and the echoing properties of the aircraft. But if the aircraft makes its approach at the low altitude of 300 m (1000 ft) it will not come into the line-of-sight to the radar until it is within 80 km of the ship. Thus, the coverage of the ship's radar is severely limited by the curvature of the earth, both for detection of surface targets and low-flying aircraft.

About the most favourable site imaginable for a ground-based radar would be on a mountain 3000 m above sea level, and looking out over the sea. In this case the geometric line-of-sight from the radar becomes tangent to the sea surface at a horizon

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[38] Neglecting obstacles in the atmosphere, such as clouds or aerosols.

[39] Refraction of the radar energy will often extend the horizon, and therefore the maximum range, beyond the 18 km. In this treatment we assume the radiation to travel in straight lines, which is very accurate in empty space, for the upper atmosphere, and for penetration of the lower atmosphere at other than nearly horizontal angles.

distant 200 km, and then beyond that rises above an altitude of 300 m at a range of 250 km. Compared to the radar on the ship, its coverage is very much better against surface targets (200 km vs. 18 km), and much better against low-flying aircraft (250 km vs. 80 km for a target 300 m above the sea).

Figure I shows three diagrams, all on the same scale, of geometrical coverage of the earth and lower atmosphere. The top diagram represents the radar on the mountain, with the geometrical line-of-sight touching the horizon at a range of 200 km, and passing out of the lower atmosphere, which is taken to have its ceiling at an altitude of 20 km (66,000 ft) at a range of 700 km. In the distance of 1000 km shown on Figure I, the curvature of the earth is hardly distinguishable[40], but nevertheless it is responsible for the horizon at 200 km, and the zone below the line-of-sight which is hidden from the radar. A large early warning radar might be able to detect air targets in the shaded zone above the line out to ranges of perhaps 500 km, but it has not been the general practice to extend the range capability beyond this when the purpose is to detect air targets.

If the sensor is mounted in a jet-propelled aircraft it should be possible to lift it to an altitude of up to 11.6 km (38,000 ft), which puts the geometric horizon at a range of 380 km. Radar mapping of large features of terrain should be possible over much of the area within this range limit. But the best photography and results from other sensors for observing the earth's surface will usually be confined to directions much closer to the vertical, and for both radar and optical sensors observations of the earth's surface are badly degraded when the line-of-sight is nearly horizontal.

There are two reasons for this. One is that the radiation must pass through long distances in the lower atmosphere, where it is subject to absorption and scattering by clouds, haze, aerosols, or dust. The other reason is that many objects on the ground will be screened by taller objects, including hills and buildings. As a rule of thumb it is often

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40 On charts of vertical radar coverage it is customary to exaggerate the vertical scale with respect to the horizontal. On each diagram of Figures I and II the vertical and horizontal scales are the same. This demonstrates the fact that long-range tracking of air targets is carried out at very low angles of sight.

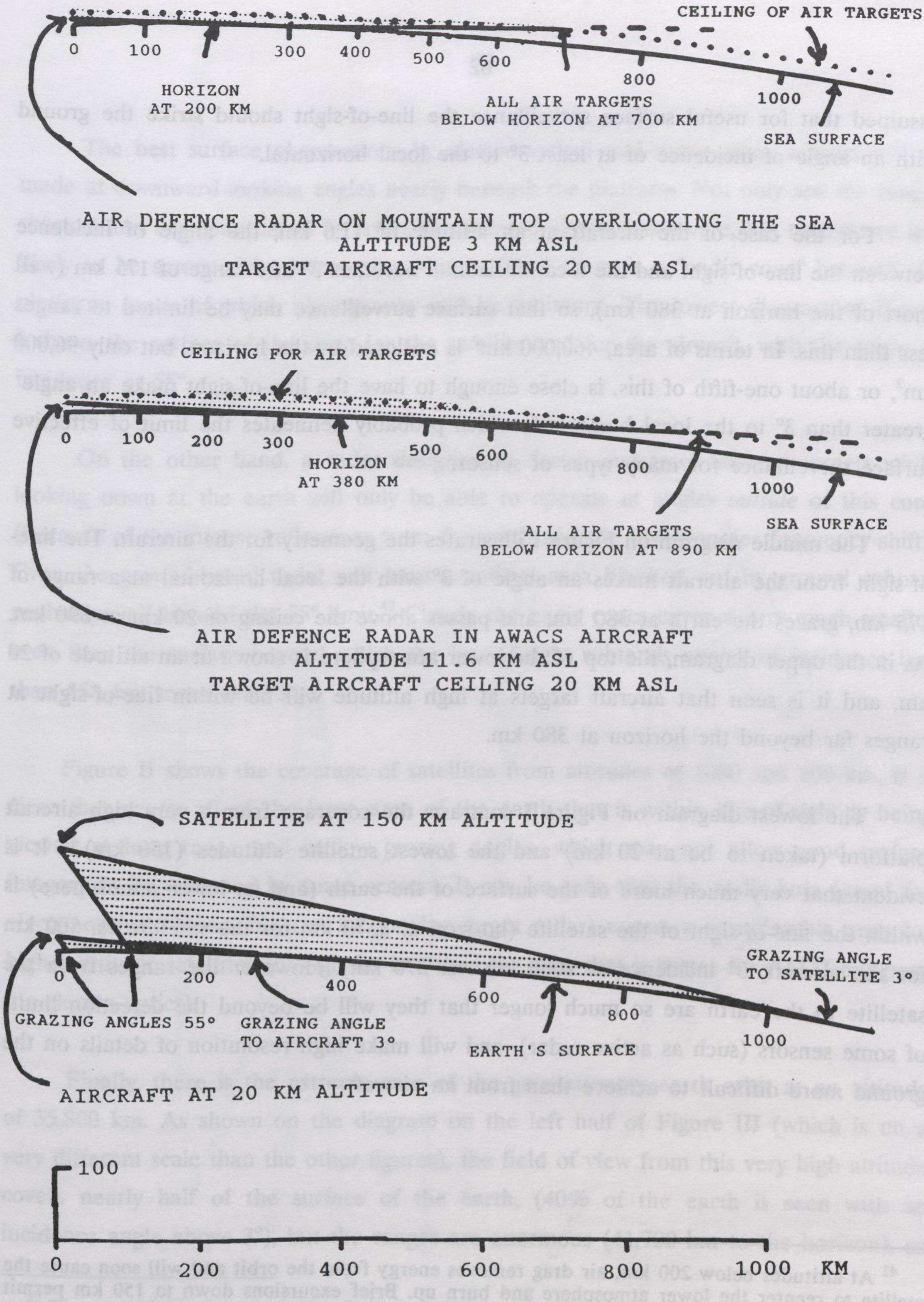

FIGURE I

FIELDS OF VIEW FROM MOUNTAIN, AIRCRAFT, AND SATELLITE

assumed that for useful surface surveillance the line-of-sight should strike the ground with an angle of incidence of at least 3° to the local horizontal.

For the case of the aircraft at an altitude of 11.6 km, the angle of incidence between the line-of-sight and the local horizontal becomes 3° at a range of 175 km (well short of the horizon at 380 km), so that surface surveillance may be limited to ranges less than this. In terms of area, 460,000 km^2 is enclosed by the horizon, but only 96,000 km^2, or about one-fifth of this, is close enough to have the line-of-sight make an angle greater than 3° to the local horizontal, which probably delineates the limit of effective surface surveillance for many types of sensor.

The middle diagram on Figure I illustrates the geometry for the aircraft. The line-of-sight from the aircraft makes an angle of 3° with the local horizontal at a range of 175 km, grazes the earth at 380 km, and passes above the ceiling of 20 km at 890 km. As in the upper diagram, the top of the lower atmosphere is shown at an altitude of 20 km, and it is seen that aircraft targets at high altitude will be within line-of-sight at ranges far beyond the horizon at 380 km.

The lowest diagram on Figure I contrasts the coverage from a very high aircraft platform (taken to be at 20 km) and the lowest satellite altitudes (150 km).[41] It is evident that very much more of the surface of the earth (and its lower atmosphere) is within the line-of-sight of the satellite (horizon at 1370 km for the satellite vs. 500 km for the aircraft; 3° incidence at 1080 km, vs. 270 km). However the ranges from the satellite to the earth are so much longer that they will be beyond the detection limits of some sensors (such as active radar), and will make high resolution of details on the ground more difficult to achieve than from an aircraft.

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[41] At altitudes below 200 km, air drag removes energy from the orbit and will soon cause the satellite to reenter the lower atmosphere and burn up. Brief excursions down to 150 km permit better observations to be made.

The best surface observations by electro-optical and some other sensors will be made at downward-looking angles nearly beneath the platform. Not only are the ranges shortest and the obscuration by layers of scattered clouds less severe, but targets are less likely to be screened by intervening objects. Thus there is a "nadir cone" beneath the platform, *inside* of which photography will be optimum. The lowest diagram of Figure I shows the surface of the cone for the satellite and for the aircraft, with the angle of incidence at 55°.

On the other hand, a radar designed to detect and track moving targets while looking down at the earth will only be able to operate at angles *outside* of this cone (because of the intense reflections from the earth and the low Doppler frequency shift). Even the ground-based radar will have a central area blanked out by ground echoes, probably well beyond the 55° limit.[42] Clearly the nadir cones cover a very much smaller area than the surface beyond which the line-of-sight subtends angles of incidence less than 55°, but more than 3°.

Figure II shows the coverage of satellites from altitudes of 1000 and 200 km. It is clear that nearly all of the large area of the earth that is within line-of-sight is being viewed at long range and at low grazing angles, which may not allow good surface imagery to be collected by some sensors. It can be seen that the nadir hole (good for electro-optical sensors but not for moving target radar) covers a considerable area for higher altitude satellites (though far less than the area that is better for AMTI but poor for electro-optics).

Finally, there is the extreme case of the geostationary earth orbit at an altitude of 35,800 km. As shown on the diagram on the left half of Figure III (which is on a very different scale than the other figures), the field of view from this very high altitude covers nearly half of the surface of the earth, (40% of the earth is seen with an incidence angle above 3°), but the ranges are enormous (41,700 km to the horizon), so

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[42] The area blanked out by ground clutter will be reduced if the radar operates with MTI.

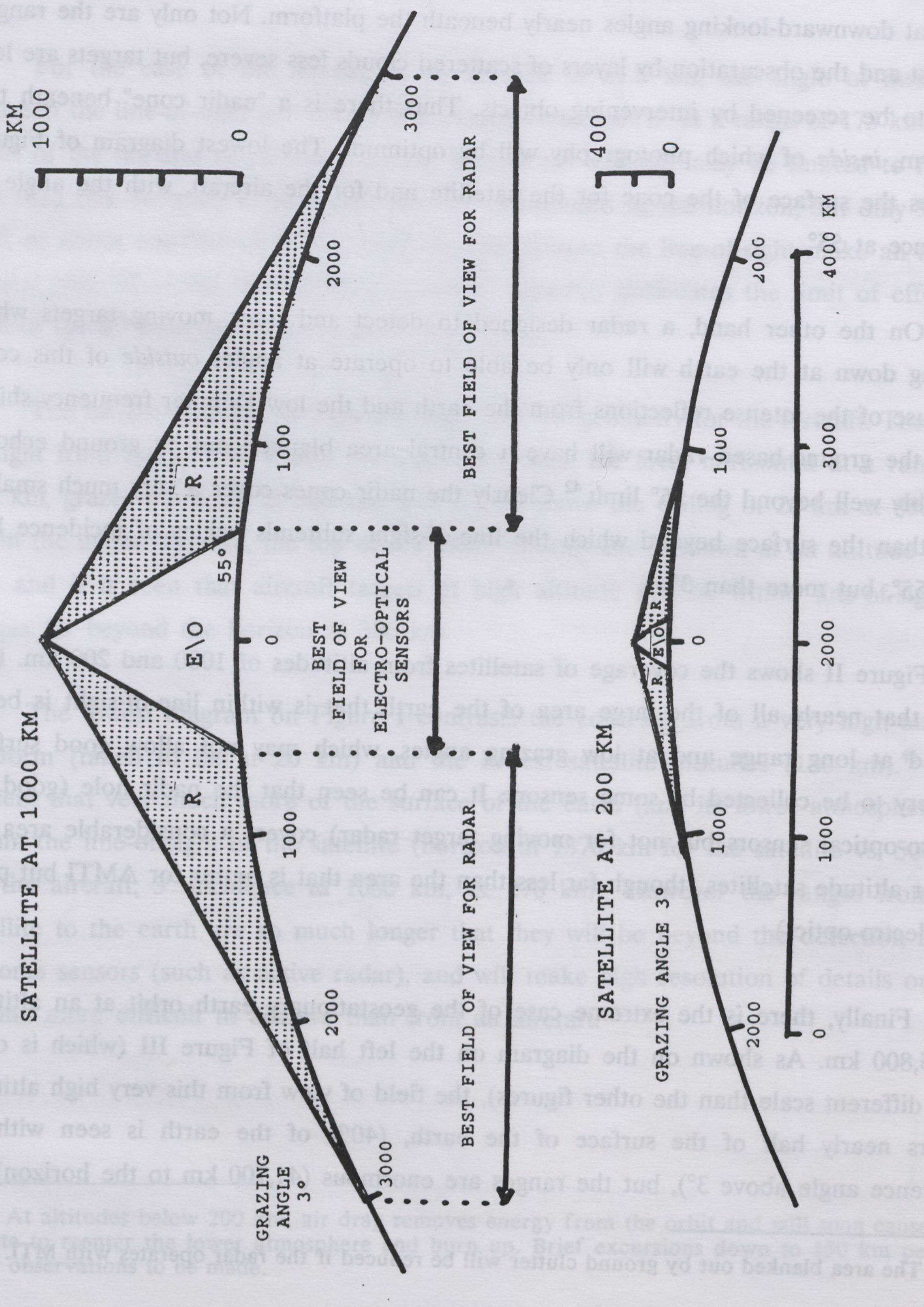

FIGURE II

BEST FIELDS OF VIEW FROM LOW EARTH ORBIT FOR ELECTRO-OPTICAL AND RADAR SENSORS

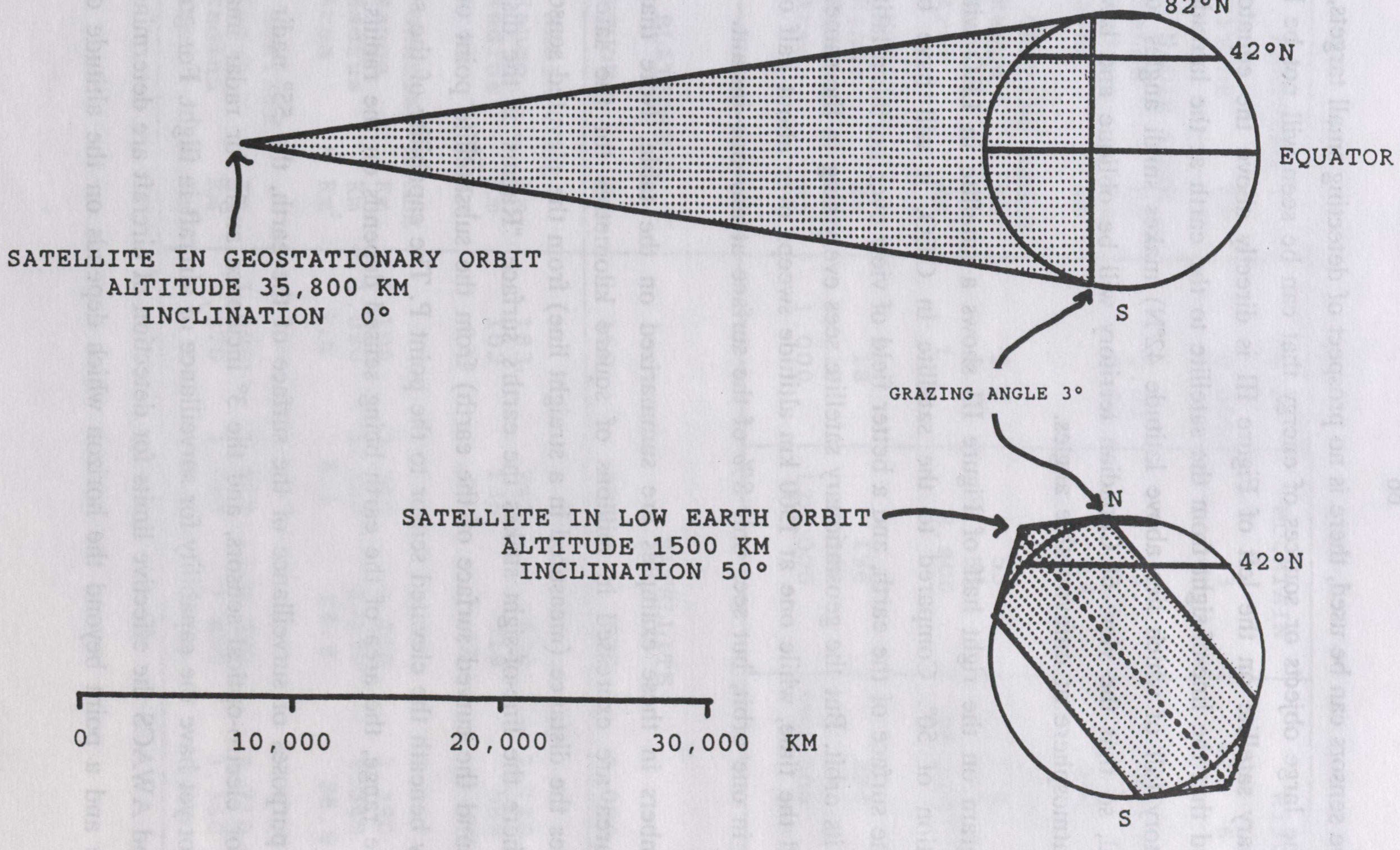

FIGURE III

FIELDS OF VIEW FROM GEOSTATIONARY AND FROM LOW EARTH ORBITS

that only passive sensors can be used, there is no prospect of detecting small targets, and resolution of the large objects or sources of energy that can be seen will not be high. The geostationary satellite on the left of Figure III is directly above the equator. It should be noted that the line-of-sight from the satellite to the earth at the latitudes of Canadian territory (all of which lies above latitude 42°N) makes small angles to the local horizontal, so that the view of Canadian territory will be oblique and have to penetrate the atmosphere at unfavourable angles.

The diagram on the right half of Figure III shows a satellite in LEO with an orbital inclination of 50°. Compared to the satellite in GEO, it will have better resolution of the surface of the earth, and a better field of view over northern latitudes during part of its orbit. But the geostationary satellite sees everything in the same 40% of the earth all the time, while one at 1500 km altitude sweeps over about half of the earth's surface in one orbit, but sees only 8% of the surface at any one instant.

The numbers in these examples are summarized on the table. Note that the numbers for area are expressed in millions of square kilometres for the satellites. "Range" signifies the distance (measured in a straight line) from the elevated sensor to the point P where the line-of-sight strikes the earth's surface. "Radius" is the distance (measured around the curved surface of the earth) from the subsatellite point on the surface directly beneath the elevated sensor to the point P. The capability of the sensor depends on the range, the area of the earth being sensed depends on the radius.

For the purposes of surveillance of the surface of the earth, the 55° nadir cone is significant for electro-optical sensors, and the 3° incidence angle for radar imagery. Satellites do not yet have the capability for surveillance of aircraft in flight. For ground-based radar and AWACS the effective limits for detection of aircraft are determined by the nadir hole and a point beyond the horizon which depends on the altitude of the aircraft.

PLATFORM :		SHIP	MOUNTAIN	AIRCRAFT	
ALTITUDE	Km:	0.025	3	11. 6	20
55° NADIR CONE					
Range	Km	0.03	3.7	14	24
Radius	Km	0.02	2.1	8	14
Area	Km^2		14	206	610
3° GRAZING ANGLE					
Range	Km	0.4	53	176	272
Radius	Km	0.4	53	175	271
Area	Km^2	1	8,800	96,000	230,000
0° HORIZON					
Range	Km	18	196	384	505
Radius	Km	18	196	384	504
Area	Km^2	1,000	120,000	463,000	798,000

PLATFORM :		SATELLITE				
ALTITUDE	Km:	150	200	500	1 000	35,786
55° NADIR CONE						
Range	Km	183	242	600	1,180	36,780
Radius	Km	102	135	319	588	3,340
Area	M Km^2	.033	.057	.32	1.08	34
3° GRAZING ANGLE						
Range	Km	1 100	1 310	2,260	3,390	41,350
Radius	Km	1,080	1,280	2,130	3,040	8,720
Area	M Km^2	3.6	5.1	14.2	28.5	204
0° HORIZON						
Range	Km	1,390	1,610	2,570	3,710	41,680
Radius	Km	1,370	1,580	2,450	3,360	9,050
Area	M Km^2	5.9	7.8	18.6	34.6	217

TABLE

FIELDS OF VIEW FROM ELEVATED PLATFORMS

Coverage from Moving Sensors

From an altitude of 11.6 km an aircraft can view an area of about 460,000 km^2 out to the geometrical horizon, 96,000 km^2 with an angle of incidence greater than 3°, but only 206 km^2 with the angle more than 55°. If it flies for twelve hours at a speed of 700 km\hr it will "sweep" over areas on the earth's surface of 6,450,000, 2,920,000, and 141,000 km^2 extending out to the three incident angles of 0°, 3°, and 55° respectively. The total area of the Canadian land mass is about 9,900,000 km^2. Thus if its sensors are able to detect out to the 3° incidence limit, one aircraft has the potential to provide one-look surveillance over all of Canada in a period of a few days.[43] But it would take dozens of sorties to cover all of Canada with near-vertical observations.

For a satellite in a circular Low Earth Orbit (LEO) at an altitude of 200 km, the geometrical horizon is 1580 km from the subsatellite point (the radius measured around the curve of the earth), and the enclosed area is 7,770,000 km^2. For the circular zones inside which the angles of incidence exceed 3° and 55°, the radii are 1280 and 135 km respectively, and the enclosed areas 5,100,000 and 57,000 km^2. The satellite overlooks more territory at low angles of incidence *and at any instant* than the aircraft covers in its twelve-hour sortie.

Taking into account the motion of the satellite (moving at up to 7.3 km/sec for low earth orbits), it sweeps the huge areas of 994,000,000, 805,000,000, and 85,000,000 km^2 every twelve hours, hundreds of times the sweep rates of the aircraft. Although the field of view within the satellite's nadir cone is only 57,000 km^2, it takes it less than 2 minutes to sweep the 141,000 km^2 that can be covered by the aircraft in twelve hours. However, this sweeping is made over most of the globe, and only a small proportion of it over any specified area of prime interest (such as the 9,900,000 km^2 of Canadian

[43] It would probably be possible to detect signals from every radio navigation beacon in Canada in two sorties. But most sensors cannot produce useful observations of the ground out as far away as the geometrical horizon.

territory[44]), whereas the aircraft would spend nearly all of its sortie over the area of interest. Surveillance from GEO is a special case, providing continuous cover over nearly half of the earth, but with very low resolution.

It must be emphasized that most sensors will not be able to observe all (or even nearly all) of the field of view available from their elevated position. Imaging sensors can exchange resolution for wide area views. Atmospheric scattering or absorption will block large areas. If daylight or particular sun angles are desired, large portions of each orbit may be unproductive.[45]

Figure IV illustrates the coverage accumulated in twenty-four hours by a satellite in LEO with an orbital inclination of 75° and able to observe a swath about 150 km across. It is seen that ten of the sixteen orbits cross some part of Canada, but that only a small fraction of its area is under a swath. The coverage is denser over the latitudes near 75°N, but increasingly sparse farther south.[46] The speed of the sweeping is indicated by the hatch marks on the seventh orbit, representing intervals of two minutes.

Advantages of the satellite rest in its larger field of view of the surface of the earth, the faster velocity with which it sweeps over the earth[47] (except for satellites in very high orbits), and the fact that once launched it continues to orbit for a long time. A disadvantage is the very limited freedom to manoeuvre out of the fixed orbit.

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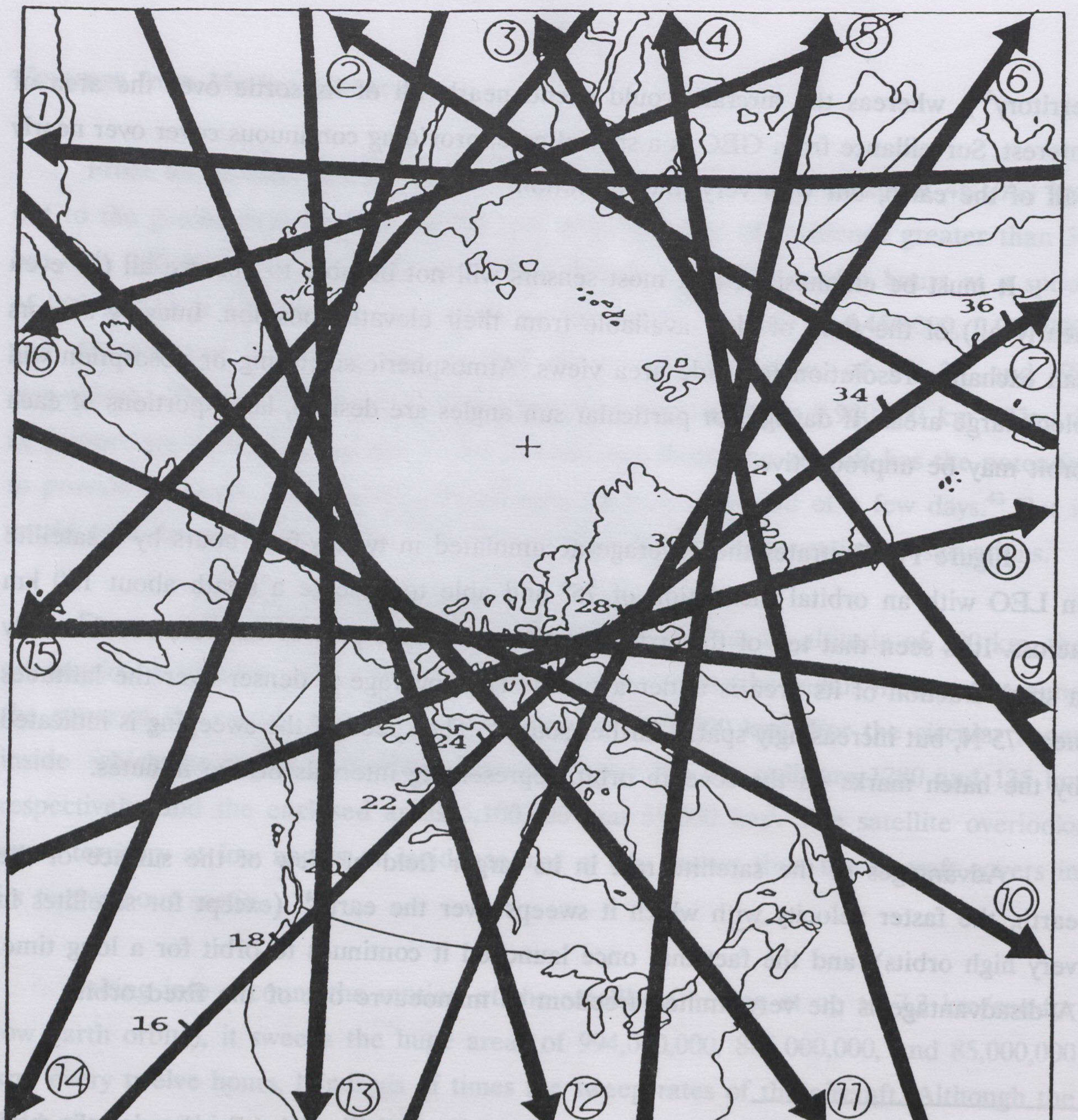
[44] The Canadian landmass covers about 2% of the area of the globe. By choosing the most favourable (near polar) orbit it would be possible to have a satellite over Canada as much as 7 % of the time, but no more.

[45] A near-polar sun-synchronous orbit allows its sensors to observe the earth with the same sun angles throughout the year.

[46] For a description of the relationship between orbital parameters and coverage of Canada, see *Surveillance over Canada*, by G R Lindsey and G E Sharpe, Working Paper No.31, Canadian Institute for International Peace & Security, Ottawa, 1990, pp.33-48.

[47] The ratio of the areas covered instantaneously from a satellite as compared to an aircraft varies from about 20 to the geometrical horizon, to around 50 for the area inside of which the angle of incidence is greater than 3°, but is much larger (around 250) for the nadir cone. The ratio of speeds is around 40.



Inclination = 75° Period = 91 minutes

Swath Width 150 km

FIGURE IV

TWENTY-FOUR HOURS' COVERAGE

An important advantage of the aircraft is that it spends all of its time in the area of interest,[48] and can be diverted to pay particular attention to some sub-area of special interest, remaining there to provide continuous surveillance for several hours if necessary. Also, the path of the aircraft can be chosen to maximize the time spent in clear air masses or beneath cloud cover.

[48] Except for the time to get from its base to the area of interest, and to return.

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