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The Role of Astronomical Instruments in Arms Control Verification

by

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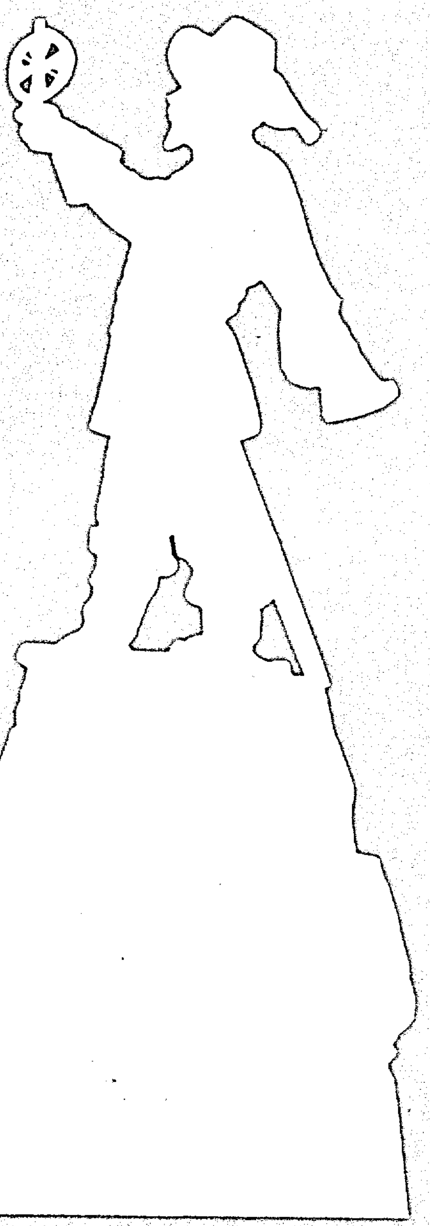

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Probably the first astronomical instrument used in Canada, the astrolabe of Samuel de Champlain, the father of New France and hence of Canada, was lost on a journey of exploration near Ottawa in 1613. Some 254 years later, in 1867, it was recovered and is commemorated in the statue represented on the cover, which stands in the shadow of Parliament Hill overlooking the Ottawa River.

The graphic on the cover page represents the ongoing dialogue on arms control and disarmament issues in Canada and between Canadians and the world community.

Arms Control Verification Studies

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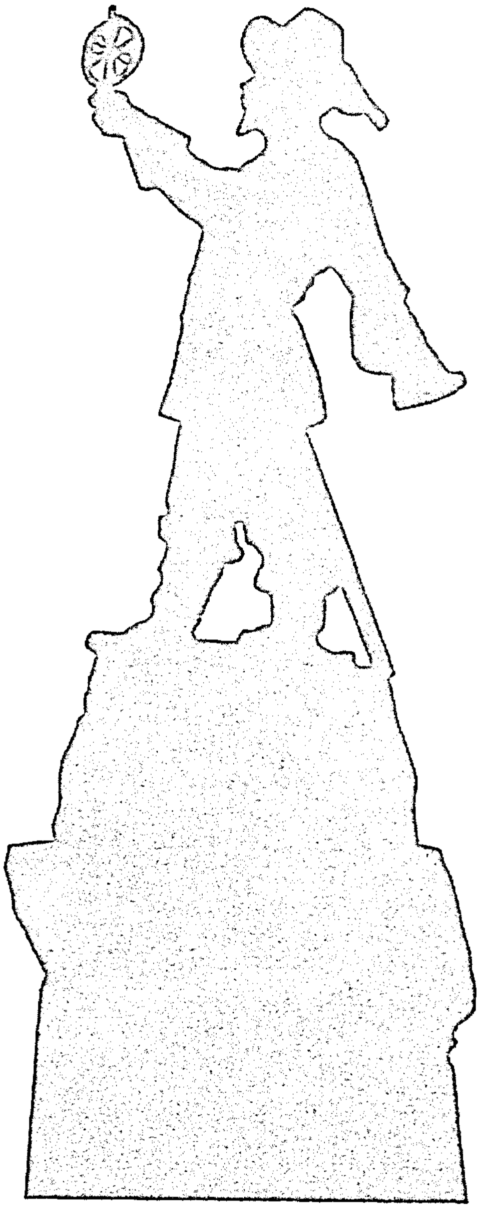

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Table of Contents

Abstract

Astronomical instruments and methods have become increasingly used in military space research. It is also quite possible to use these same techniques for verifying arms control agreements related to space-based weapons and ground-based deployment of troops and weapons.

Early satellite tracking programs are described, including: "MOONWATCH" which involved the use of civilians making visual observations, the Baker-Nunn camera system, photometric observation systems and the Ground-Based Electro-Optical Deep Space Surveillance (GEODSS) system. There follows a short section outlining the resolution potential of various optical and radar systems.

The author then discusses developments in the area of space-based weapons, including Fractional Orbital Bombardment Systems (FOBS) as well as Directed Energy and other Anti-Satellite (ASAT) weapons. International agreements relating to the militarization of space are reviewed and the role of ground-based and space-based systems for monitoring these and other treaties is reviewed.

Among the author's observations are:

1. Satellite tracking is likely to become more important as the military use of space increases.
2. Proposals for arms control verification in space should include the use of technology at the same level as the systems to be verified.
3. As Baker-Nunn cameras used by the military are replaced by electro-optical systems, their transfer to astronomical institutions would be useful in the development of verification techniques in the academic sector.
4. Spin-offs from military astronomical technology development should be realized by scientific institutions for asteroid tracking, binary-star resolution, quasar studies and other projects.
5. Canada stands in a good position to contribute to ground-based verification studies on an international scale and possesses the necessary technical means, manpower and facilities to remain in such a position for the long term.
6. If additional GEODSS stations were to be established, it would be useful to consider Canada as a possible site.
7. Canadian astronomy, one of Canada's most prized scientific strengths, has been undermined by lack of modern equipment. If Canada participates in advanced technology projects, one spin-off advantage of such participation could be the application of astronomical technology to the verification of arms control agreements.

Résumé

L'emploi des instruments et des méthodes astronomiques se répand dans la recherche spatiale à des fins militaires. En outre, il y a de nombreuses possibilités d'application de ces mêmes techniques à la vérification des accords de contrôle des armements ayant trait aux armes basées dans l'espace ainsi qu'au déploiement terrestre de troupes et d'armes.

L'auteur décrit les premiers programmes de poursuite des satellites, dont le réseau «Moonwatch», qui prévoyait des observations visuelles par des civils, le système de caméra Baker-Nunn, les réseaux d'observation photométriques et le système de Surveillance terrestre électro-optique de l'espace lointain (GEODSS = Ground Based Electro-Optical Deep Space Surveillance). Suit alors une brève section sur la capacité de résolution de divers systèmes optiques et radars.

L'auteur examine ensuite l'évolution des armes basées dans l'espace, notamment les systèmes de bombardement à orbite fractionnaire (FOBS = Fractional Orbital Bombardment Systems) ainsi que les armes à énergie dirigée et autres armes anti-satellites (ASAT), puis il passe en revue les accords internationaux concernant la militarisation de l'espace et examine le rôle que jouent les systèmes terrestres et spatiaux dans la surveillance de ces accords et autres traités.

Voici quelques-unes des conclusions de l'auteur :

1. La poursuite des satellites prendra vraisemblablement plus d'importance à mesure qu'augmentera l'utilisation de l'espace à des fins militaires.
2. Des propositions visant la vérification du contrôle des armements dans l'espace devraient comprendre l'utilisation de la technologie sur le même plan que les systèmes devant être vérifiés.
3. Vu que les caméras Baker-Nunn qui étaient utilisées à des fins militaires sont remplacées par des systèmes électro-optiques, leur transfert à des établissements se spécialisant dans le domaine de l'astronomie serait fort utile à la mise au point de techniques de vérification dans le secteur académique.
4. Les institutions scientifiques devraient pouvoir profiter, à partir de la technologie astronomique militaire, de retombées pour la poursuite des astéroïdes, la résolution des étoiles binaires, l'étude des quasars et d'autres projets.
5. Le Canada est bien placé pour contribuer aux études sur la vérification à partir de la Terre, à l'échelle internationale; il possède les moyens techniques, la main-d'oeuvre et les installations nécessaires pour garder cette position de façon permanente.
6. Si de nouvelles stations GEODSS étaient mises sur pied il serait bon de considérer le Canada comme site éventuel.
7. L'astronomie canadienne, l'un de nos atouts scientifiques les plus précieux, manque de matériel moderne. Si le Canada participe à des projets de technologie avancée, une des retombées de cette participation serait l'application de la technologie astronomique à la vérification des accords sur le contrôle des armements.

Introduction

The space age is said to have begun when the first Sputnik was launched in 1957. Since then, many payloads have been orbited. The present number of objects in orbit is about 5,000.

With the deployment of satellites and space platforms for military use, astronomers have found their previously uncontested domain "invaded" for non-scientific purposes. Because many applications involve observational techniques, it is not surprising that astronomical instruments and methods have become increasingly used in military space research.

Along with the military aspects of astronomy comes the possibility of using these same techniques to aid in the verification of space-based weapons systems and the ground-based deployment of troops and weapons. This possibility shows some promise, with certain limitations dependent on arms control agreements and defence policies.

Chapter One

Visual Observations of Satellites

In July 1956, the Smithsonian Astrophysical Observatory (SAO) issued its first *Bulletin for Visual Observers of Satellites* as an introduction to amateur astronomers registered in its then unnamed visual observing program. Eventually called MOONWATCH, the program was initiated to assist the SAO in the preliminary tracking of satellites launched during the International Geophysical Year. Although Baker-Nunn telescopes were at that time under development for photographic tracking, the initial orbital path was needed before the Baker-Nunns could be employed. Radio tracking was also used when possible, although the failure of instrument packages was expected, and optical techniques were employed to relocate "lost" satellites. Optical observations of satellites were thus a necessary part of early satellite tracking.

The advent of the Soviet Union's Sputnik in October 1957 showed how valuable the MOONWATCH program really was. In its Bulletin for March 1958, its Associate Director, J. Allen Hynek (best known, ironically, for his involvement in "UFO" research) commented that "the unexpected appearance of the Russian Sputniks and their high inclinations to the equator have made it necessary for MOONWATCH teams to act as interim tracking stations until our full complement of precision satellite tracking cameras is in position".[1] In fact, the problem was somewhat more complicated. The Russian launches were at precisely the "wrong" orbital inclination for many MOONWATCH stations and those Baker-Nunn cameras already in position. Stations were thus quickly set up to accommodate the higher orbital inclinations.

Optical observations tend to be more accurate in principle than radio measurements because of ionospheric distortion, although compensatory mechanisms are used for radio tracking. Removing human error from observation greatly improves the accuracy, of course, so the development of Baker-Nunn cameras was a major step forward. The MOONWATCH program, however, was not officially disbanded until June 30, 1975, having been phased out in stages over the years. MOONWATCH provided a wealth of valuable data during its operation; probably the most notable was the observation of the re-entry and the recovery of Sputnik 4 on September 5, 1962, over Wisconsin. Other data for MOONWATCH came from the Volunteer Flight Officers Network, whereby airline personnel made over 4,000 observations of satellites and meteors.[2]

At its termination, MOONWATCH still had 100 active stations. It was described as the least expensive part of the space program, utilizing only $14 million for the duration of its operation. This is significant, especially since it was originally intended to operate for only 18 months. Instead it operated for 18 years, giving valuable information on satellites throughout its existence.[3]

Some note should also be made of the amateur radio tracking of satellites, carried on by various groups. The most successful of these has been a group in Kettering, England, which has been monitoring satellite telemetry and interpreting its meaning for several years. The Kettering group showed exactly how valuable an amateur tracking operation could be when it discovered the secret Russian Plesetsk launch site, something Western experts had only guessed at. What is more, the group accomplished this with only store-bought shortwave receivers.[4]

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[1] See Hynek, J.A. *Bulletin for Visual Observers of Satellites*, no. 8, May 1958. In: *Sky and Telescope*, V. 17, no. 3, Sept. 1975, pp. 160-163.

[2] A history of the MOONWATCH program is given by J. Cornell, "The MOONWATCH Era Ends", *Sky and Telescope*, V. 50, no. 3, Sept. 1975, pp. 160-163.

[3] Many Canadian astronomers participated in the MOONWATCH program. Details on the participation of the Winnipeg Centre of the Royal Astronomical Society of Canada, for example, are given in Hladiuk, D., "Project MOONWATCH", in: Belfield, P., ed. *A History of the Winnipeg Centre, RASC, 1911-1977*, Ch. 3, RASC, Winnipeg, 1977.

[4] The Kettering group has received considerable attention recently. A summary of its activities and biographic reviews can be found in: Peebles, C. "Satellite Radio Tracking for the Amateur", *Spaceflight*, V. 25, Dec. 1983, pp. 459-60; and Solomon, S. "Eavesdropping on Soviet Satellites", *Science Digest*, V. 92, no. 1, Jan. 1984, pp. 32, 36, 81.

Chapter Two

Photographic Observations of Satellites

The Baker-Nunn camera was developed at about the same time as the MOONWATCH program. Its optics were designed by James G. Baker who was the inventor of the Super-Schmidt meteor camera. The mount and drive were developed by Joseph Nunn. Twelve such cameras were produced by the Perkin-Elmer Corporation of Connecticut and installed in locations around the globe. The first became operational in New Mexico, in November 1957, a full month after Sputnik 1 was launched. For that month, orbital data were available only through MOONWATCH stations. It is probably this fact that spurred the rapid development of satellite tracking technology in the following years.

Baker-Nunn systems are best suited for detecting high-altitude satellites, up to 40,000 km or more. Because of this, they complement radar tracking systems which are restricted to altitudes of less than 7,000 km. Baker-Nunn cameras are passive systems detecting the reflected light of satellites against the background of stars. Once a general set of coordinates is identified, a photograph is taken. The objects on the photograph are compared with a star chart using an overlay, and a satellite's position is noted. Successive photographs can determine the orbit of the satellite to within about 30 seconds of arc and in some cases to 2 or 3 seconds of arc. The position of the satellite is reported to the Space Defense Center so that the NORAD computer catalog can be updated.[5]

The major problem with the Baker-Nunn system is that the time required to develop the film may be as long as 90 minutes. That is certainly inadequate for rapid tracking and orbit determination since some satellites can change orbit in a shorter time. Ideally, information should be available in a time frame much closer to real-time to permit early warning of sudden orbit changes.

The limiting magnitude (i.e. the faintest apparent magnitude that may be observed) of the Baker-Nunn camera is also relevant to its capability for satellite tracking. This limiting magnitude is dependent on several variables, including zenith distance, the angular velocity of the photographed object, its visual magnitude and the sensitivity of the film emulsion. Another factor is the exposure time, which is inversely related to the magnitude. For an exposure at one second as a standard, the visual magnitude varies between $m = 12$ and $m = 14$, depending on the film used, which at many stations was Kodak Royal-X Pan.[6]

Most satellites have magnitudes averaging about $m = 14$, and they therefore fall within the range of the Baker-Nunn system. (The limiting magnitude for the human eye is about $m = 7.5$.)

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[5] Various studies of the Baker-Nunn system have been published. For example, see Solomon, L.H. "Some Results at Baker-Nunn Tracking Stations", *SAO Special Report*, no. 244, 1967.

[6] A rather thorough description of optical and photographic tracking systems can be found in Veis, G. "Optical Tracking of Artificial Satellites", *Space Science Reviews*, V. 2, 1963, pp. 250-296.

Chapter Three

Photometric Observations of Satellites

Early in the history of satellite tracking, the problem of detection capabilities was realized and possible solutions were investigated. Russian scientists were among the first to explore alternatives to photographic tracking, as long ago as 1960.[7]

The only difference in the tracking hardware for photometric as opposed to photographic systems is the recording medium which consists of a photon counter coupled to a computer. Such devices are comparable to those used in astronomical research for investigations into distant objects such as quasars. Unlike photographic stations, however, photometric systems require more versatile tracking mechanisms because of the small area of the photocathode. This is important for tracking objects of magnitude less than $m = 11$.

Canada's involvement intensified when the Satellite Identification and Tracking Unit (SITU) was officially opened at the St. Margaret's Canadian Forces Station near Moncton, New Brunswick, on November 9, 1976. Its chief feature is an f/16, 61-cm Cassegrain telescope mounted on a modified Baker-Nunn triaxial support. This installation was intended to replace a Baker-Nunn photographic system at Cold Lake, Alberta, and followed an exhaustive ten years of testing at the USAF Avionics Laboratory on Wright-Patterson AFB. The light from an object is relayed through the telescope's optics to the photocathode which converts the incident photons to electrons. These electronic pulses are then recorded on paper or magnetic tape for further processing; they can also be sent to NORAD over telephone lines for analysis.[8]

With an increasing number of satellites in orbit, the necessity of an additional tracking unit such as the St. Margaret's station was obvious. The St. Margaret's station was also heralded for its "semi-automatic" features. In addition to the photometric system at St. Margaret's, there is a Baker-Nunn camera on loan from the SAO site at Alisfantsfontaine, South Africa. The camera can hold 1,000 linear feet of film which can be processed at SITU at a rate of 5½ feet per minute. The photographic system is described as being able to detect a "basketball at a distance of about 20,000 miles".[9]

The interpretation of photometric measurements of satellites has provided a wealth of data to scientists. This has come about through revelations concerning the density of the Earth's atmosphere and its actual composition. But scientific information about the satellites themselves is also easily discerned from the data. It is possible to determine the rate of rotation of a satellite, its shape, size, and the reflective properties of its surface. Fluctuations in brightness were first noted by observers of booster rockets, making it simple to speculate upon their altitude and lifetime.

There have been a large number of studies of orbiting satellites based on various observations, resulting in detailed calculations of their orbits. For example, between May 1971 and June 1972, over 1,500 optical and radar observations were compiled for Cosmos 387. Included were observations from Hewitt cameras (a variation of the Baker-Nunn system), kinetheodolites, MOONWATCH stations and radar installations. Only through the combination of all these observations was it

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[7] The great Russian astronomer, I.S. Shklovskii, described photometric tracking in "Optical Methods for the Observation of Artificial Earth Satellites", *Artificial Earth Satellites*, V. 1, 1960, pp. 55-63.

[8] Kissell, K.E. and Mavko, G.E., *The Canadian Forces/ NORAD Satellite Identification Sensor at St. Margaret's*, USAF Avionics Lab., Wright-Patterson AFB, Ohio, AFAL TR-77-189.

[9] Wooding, B. and Spruston, T.A. "The Canadian Armed Forces and the Space Mission", *Canadian Defence Quarterly*, V. 5, no. 2, Winter, 1975, pp. 15-20.

possible to obtain an extremely accurate plot of the orbit. (Cosmos 387 was launched from Plesetsk as an unannounced payload; its visual magnitude of m = 6 makes it a relatively easy object to track.)[10]

Optical tracking stations have enabled the compilation of lists of satellites and their magnitudes. In turn, extrapolation and analyses of these lists have been used to identify the shapes and sizes of satellites under observation; this has permitted the determination of detailed information on secret and otherwise unannounced payloads. For example, observation of the "flash rate" gives information on the tumbling of rocket bodies, which has allowed the histories of many satellites and/or their rockets to be accurately traced. Such data are the guide by which successes and failures of satellite missions, whether announced or unannounced, can be determined. Accuracies in orbital determination using visual observations tend to be in the range of only a few metres.

One widely-published photograph clearly showed the "hammerhead" appearance of Sputnik 2, although it was taken with a 24-inch tracking telescope with a 500-inch focal length that managed to capture the satellite at a range of 200 miles.[11] The photograph was taken in 1957 with a purely optical system. Satellite measurements and imaging systems in the 1980's are much more sophisticated.

Chapter Four

Ground-Based Electro-Optical Deep Space Surveillance (GEODSS)

During the 1960's, it became apparent to individuals involved in satellite tracking that there were inherent problems with conventional tracking systems. Radar was either of insufficient resolution or of too short a range to satisfy upcoming program requirements for the greatly detailed surveillance of satellites. Similarly, optical systems had insufficient accuracy, sensitivity and speed. A major problem with optical systems was their inability to cope and function in real-time. But in the 1970's, with developing silicon diode technology and the dawn of the age of micro-processors, several laboratories were assigned the task of designing a *real-time* photoelectric system for satellite tracking. A design was accepted in 1974, and in September 1975, an experimental test site was put into operation at the White Sands Missile Range near Socorro, New Mexico. It was the first station in the GEODSS program developed by the USAF Systems Command. In 1979, the cost of installing a network of five sites was set at $62 million. The second and third sites are at Taegu, South Korea, and on Mount Haleakala, on Maui, Hawaii. A fourth site is presently being installed on the island of Diego Garcia in the Indian Ocean. Construction on a fifth site is expected to begin by 1985 "somewhere along zero degrees longitude in the eastern Atlantic", possibly in Portugal or on Ascension Island. (Original plans for the fourth and fifth GEODSS sites had called for installation in Iran and Morocco.)[12] The GEODSS system was given five major missions: 1) initial detection, 2) tracking, 3) catalog maintenance, 4) collection of

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[10] Many studies of individual satellites have been published in the journal *Planetary and Space Science*. In particular, King-Hele and Pilkington have performed detailed analyses of optical tracking. See King-Hele, D.G., "Analysis of the Orbit of Cosmos 387 (1970-111A). Near 15th-order Resonance", *Planetary and Space Science*, V. 22, pp. 509-524; and Pilkington, J.A. "The Visual Appearance of Artificial Satellites", *Planetary and Space Science*, V. 14, 1966, pp. 1281-1289.

[11] Published by Stine, G.H. "How the Soviets Did It In Space", *Analog*, V. 81, no. 6, Aug. 1968, pp. 48-71.

[12] Details on the operation and development of the GEODSS system have been presented in a large number of publications. A good, readable summary is given by Beatty, J.K. "The GEODSS Difference", *Sky and Telescope*, V. 63, no. 5, pp. 469-473. Another important source is: Smith, B.A. "Ground-Based Electro-Optical Deep Space Surveillance System Passes Reviews", *Aviation Week and Space Technology*, 27 Aug. 1979, pp. 48-53. A considerable number of documents have been released by MIT's Lexington Lincoln Laboratory, Electronic Systems Division, at Hanscom AFB. A good review at a semi-technical level is given by Weber, R. "Passive Ground-Based Electro-Optical Detection of Artificial Earth Satellites", *Optical Engineering*, V. 18, no. 1, 1979, pp. 82-91. Specific MIT technical reports relevant to GEODSS, used as references to the following discussion, are: ESD TR-77-125; 78-33; 78-270; 79-277; 79-326; and 79-350.

brightness data, and 5) other classified tasks. The first site has a main telescope with a 31-inch mirror which is a f/5 unit with a one-degree field on a 80-mm plate. The auxiliary telescope is a 14-inch, f/1.7 Schmidt with a seven-degree field.

The operation of the system begins after dusk with calibration on a star near the probable search area using data on file. After corrections are made, if necessary, data are obtained on night-sky brightness and the atmospheric extinction coefficient (necessary for accurate brightness measurements). This procedure takes about fifteen minutes, after which a specific satellite is called up from the computer file. Slewing is done rapidly, so that the target should be in position in about one second. If the desired satellite is detected immediately, its position is recorded and the catalog is updated. If desired, the satellite can be automatically tracked and its movement recorded, either from its video output alone or using a GaAs photomultiplier.

If the satellite is not detected, search programs are initiated and continued until it is found. The programs are stored in the hardware at the site, namely a MODCOMP IV-25 which has 256 kilobytes of core memory and 25 megabytes on disk. Two major files can be easily accessed: one is a 400-element satellite catalog and the other, the SAO star catalog, has over 250,000 entries. The catalogs and the hardware are continuously updated and modified.

The system uses two types of Moving Target Indicator (MTI) hardware: one semi- and one fully automatic (MTI and AMTI). In the MTI, a video disk recorder records and plays back the incoming signal with a delay of 1 to 4 seconds so that moving satellites are readily apparent. With AMTI, a software program called ASTRO-SO automatically compares successive frames and determines "threats" which are identified by their movement against the background.

The type of detector used for the GEODSS system is an Ebsicon, which is a generic name for any camera tube containing a silicon diode target that produces an electronic signal under photon bombardment. Coupled to the Ebsicon for increased sensitivity is a single-stage image-converter tube that typically increases the detection capability by a significant factor.

The signature of a satellite, used by Space Object Identification (SOI) systems, is obtained from its pattern of varying brightness as it rotates and moves around the Earth. These signatures are stored and can be called up for comparison when needed. A change in signature is an alert to its reorientation and/or reactivation. The use of this information will be explored in a later section.

Sites other than that at White Sands have a slightly larger series of optics, each with two 1-metre main telescopes having 2.2-metre focal lengths and 2.1-degree fields. As well, each site has a third auxiliary 0.4-metre telescope with a 6-degree field. Each telescope has an 80-mm Ebsicon tube with a 32-mm target. These main telescopes have a normal limiting magnitude of $m = 16$, although they can be "pushed" to $m = 18.5$. The auxiliary systems have a limit of only $m = 14.5$ but, because of their wider field and more rapid slewing capability, they are used selectively for observations of low-altitude reconnaissance satellites.

In addition, each site has a video zoom feature which can centre on a particular section of the screen output for operator assistance. Of particular interest is the inclusion of a radiometer to monitor infrared emission from satellites. This enables satellites to be differentiated from one another and classified as payloads, boosters or fragments.[13]

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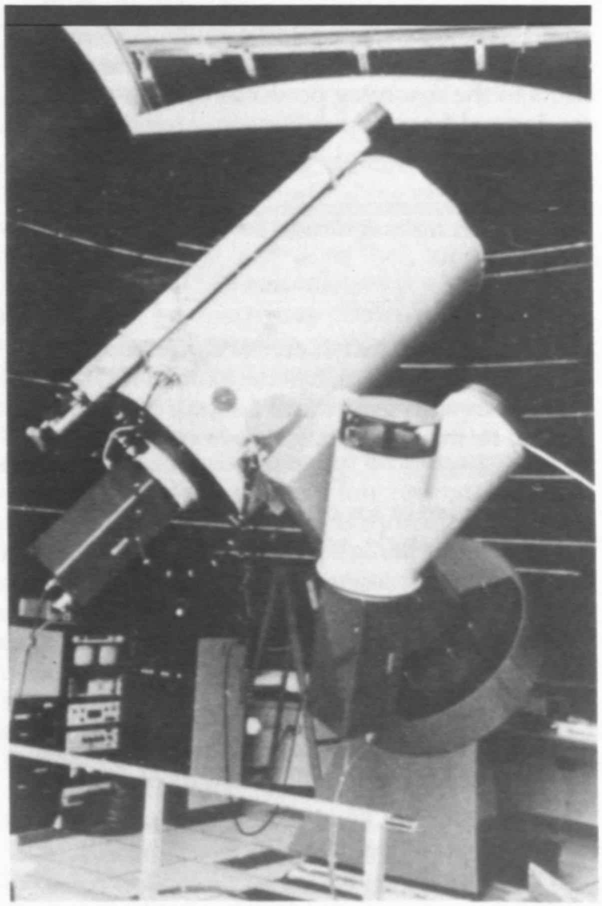
[13] McNamara, F.L. and Krag, W.E. "Radiometers for Measurements of Space Objects", MIT Electronic Systems Division, TR-79-9.

Although it is the movement of the satellites that gives them away (for example, a geosynchronous satellite moves 15 seconds of arc per second), apparently stationary satellites with a sidereal rate of revolution can be identified through comparison with star catalogs, albeit with some difficulty.

Locations of tracking sites used or noted by GEODSS are given in Appendix 1.

Recently the GEODSS sites have been further upgraded to use Digital Equipment Corporation PDP II-70 computers. ASTROSO has been refined, and the Resident Space Object Catalog (RSOC), maintained by NORAD, has been expanded to over 1,000 entries. Satellites can be identified within six seconds (complete analysis takes a full minute) and their position can be determined to within 10 seconds of arc.[14]



▲ The main telescope of the GEODSS Experimental Test Site at White Sands AFB. It has an aperture of 31 inches and is a P/5 system (from Weber, 1979).

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[14] Randolph, A. "USAF Upgrades Deep Space Technology", *Aviation Week and Space Technology*, 28 Feb. 1983, pp. 57-8.

Chapter Five

Resolution of Space Objects

Regardless of the cost and number of years under development, optical satellite systems must abide by the laws of physics. There are limits to the resolving power of optics which are derived from calculations involving the camera apertures and the observed objects themselves.

The limiting magnitude for any telescope is defined as:

$$m = 2.7 + 5 \log D$$

where D is the diameter of the aperture in millimetres. Thus, the limit for a GEODSS system with a mirror of 1-metre diameter will be $m = 17.7$, sufficient to resolve most satellites.[15]

Another factor for consideration is the smallest resolvable angle, which is defined as:

$$\phi = 120/D$$

where ϕ is given in seconds of arc. For the same GEODSS system, therefore, this angle will theoretically be about 0.12 seconds of arc. However, ϕ is limited also by the Earth's atmosphere which sets this ground-based limit at about 0.5 seconds of arc.

As an example, let us consider the case of Molniya 1, Flight 20, which is a communications satellite launched from Plesetsk on April 4, 1972. Its perigee is at a height of 480 km, and it has an apogee of nearly 40,000 km. The satellite is a cylinder 3.5 by 1.7 metres, with several "paddle wheel" solar arrays and two dish antennas. Let us assume it presents a 3-metre face towards a GEODSS station. We can calculate its angular diameter by using the relation:

$$d/h = \tan \phi$$

where d is the diameter of the satellite, h is its altitude and ϕ is its angular diameter, in degrees. When d is 3 m and h is 1,000 km, ϕ is 0.00017 degrees or 0.6 seconds of arc. This is within the capability of the GEODSS system defined in the example.

As a further example, let us use a reverse situation. Consider the "Big Bird" reconnaissance satellite of the United States. It is reportedly capable of a ground resolution (from orbit) of 150 mm. At the smallest resolvable angle, therefore, where ϕ is 0.5 seconds of arc, the altitude can be calculated to be a *maximum* of 61 km. This is obviously too low, since the maximum altitude of the Big Bird satellite is known to be about 150 km, and its perihelion cannot be 61 km as that would place it within a dense region of atmosphere. However, even for an altitude of 100 km, the resolution will be near 0.25 metres, still a respectable value (of the order of 10 inches).[16]

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[15] The limits discussed in this section are approximate values only and dependent on many variables. In general, the smallest resolvable angle is merely the wavelength divided by the aperture. Basic sources for these data include various astronomical publications, for example the *Observer's Handbook* of the Royal Astronomical Society of Canada (1983). Other sources are: Lambeck, K. "Probability of Recording Satellite Images Optically", *SAO Special Report*, no. 230, 1966; McCue, G.A., Williams, J.G. and Morford, J.M. "Optical Characteristics of Artificial Satellites", *Planetary and Space Science*, V. 19, 1971, pp. 851-868; and Veis, G. "Optical Tracking of Artificial Satellites", *Space Science Reviews*, V. 2, 1963, pp. 250-296. Curiously, one of the more useful sources on detection and resolution is Ayer, F. "Instrumentation for Unidentified Flying Object Searches", *in*: Gillmor, D.S., ed. *Final Report on the Scientific Study of Unidentified Flying Objects*, Bantam Books, N.Y., N.Y., 1969, pp. 761-804.

[16] Information on USAF photoreconnaissance satellites and their Russian counterparts comes from: Bamford, J. *The Puzzle Palace*, Penguin, N.Y., N.Y., 1983; Brown, N. "Military Uses of Satellites", *in*: Fishlock, D., ed. *A Guide to Earth Satellites*, Elsevier, N.Y., N.Y., 1971, pp. 121-133; Canan, J. *War in Space*, Berkley Books, N.Y., N.Y., 1984; Clark, P.S. "Soviet Photoreconnaissance Satellites", *Spaceflight*, V. 25, no. 6; Karas, T. *The New High Ground*, Simon & Schuster, N.Y., N.Y., 1983; and Smolder, P.L. *Soviets in Space*, Butterworth Press, Guildford & Landon, 1973. In addition, the yearbooks of TRW Space Systems in California have provided ample data for consideration.

For a photographic system, the resolution is also dependent on the emulsion. Under perfect conditions, an image of a satellite is a disk of diameter d, where

$$d = (2\lambda f)/D$$

For this calculation λ is the wavelength, f the focal length and D the diameter of the aperture of the camera. Thus, for a Baker-Nunn camera with a focal length of 500 mm and an aperture of 50 cm, the diameter of a point source will ideally be about 3 microns. However, because of the effect of the atmospheric visibility conditions, this diameter is increased by a factor of 10 so that d usually is about 20 to 40 microns for fast emulsions. Recent advances in remote sensing technology have reduced these values somewhat, so that good resolution of less than 10 microns, and often near 2 to 3 microns, can now be obtained. A Baker-Nunn camera can photograph stars of

$m = 14.5$ with a 20-second exposure.

The field of a typical Baker-Nunn camera is about 30 by 5 degrees. The scale on the film is about 2.5 microns per second of arc. Therefore, the camera will theoretically be capable of photographing an object of

$$d = (2\lambda)/s$$

seconds of arc in diameter, where s is the scale. The minimum resolvable angle is therefore about 0.5 seconds of arc.

The resolution of radar tracking systems should also be considered. Although radar tracking systems, in contrast to photographic methods, are active rather than passive systems and although they utilize a different part of the electromagnetic spectrum, the basic principles are similar to those for photographic methods. For radar, resolution is defined by the relation:

$$r = 70(\lambda/D)$$

where r is the resolving power (the minimum separation in degrees of arc required to distinguish between two objects) and D is the antenna diameter. For a radar unit with an antenna diameter of 3 m and a typical wavelength of 3 cm, the beam width is 0.7 degrees of arc. For example, the maximum distance for a 3-m antenna would be about 250 m. Therefore, two objects side by side at distances greater than 250 m will appear to be one.

The resolution of a space object is dependent on several variables: 1) the wavelength used, 2) the optics, 3) the altitude of the object, 4) its size and shape, 5) its brightness, and 6) its angular velocity. It is obvious that, for example, a wavelength of 570 nanometres is not suitable for day-time or cloudy-day observations. The resolving capability of an optical system is dependent on its focal length and aperture, the system ideally having a focal length larger than the aperture width. It is also obvious that an object in a high geostationary orbit will be less easily tracked than one in a low reconnaissance orbit. The size of the object is directly related to its brightness, which is dependent upon its albedo as well as its phase angle. The phase angle will be dependent on its angular velocity, dependent in turn on its altitude. The problem of satellite observations is thus reduced to only two aspects: the observation system and the orbit (inherently, the *purpose*) of the satellite. Present optical and electro-optical systems are able to observe all types of satellites and contribute in real-time to the NORAD SPACE-TRACK satellite catalog. Giant Phased-Array Radars like the 13-storey-high structure at Elgin AFB in Florida are limited in their resolution of high-orbiting satellites, but capable of tracking a wealth of lower satellites with advanced data processors. Photometric and photographic systems, consequently, are vital for their abilities to complement radar observations. And, with an increasing number of payloads in orbit each year, the overloading of any one system must be avoided at all costs, for both military and navigational reasons.[17]

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[17] See Wooding, B. and Spruson, T.A. *op. cit.*, note 9.

Chapter Six

Space-Based Weapons

On June 18, 1982, at the second United Nations Special Session on Disarmament (UNSSOD II) Prime Minister Trudeau called upon the world community to negotiate a treaty to prohibit the development, testing and deployment of all weapons for use in outer space. While it is generally assumed that there are at present no weapons based in space, there is and has been a considerable amount of research and development in the area of space-based weapons. This interest in the feasibility of the "weaponization" of space, as distinct from the militarization of space or the military use of space, has a reasonably long history. For example, when the Soviet Union's COSMOS 139 was launched on January 25, 1967, it was believed to be the first flight test of a Fractional Orbital Bombardment System (FOBS).

9 In theory a FOBS weapon would be launched into a low orbit, travelling over the horizon towards US bomber bases. When in range, it would fire its retro-rockets and would drop towards its target with a 1- to 3-megaton payload. While in orbit, the FOBS would resemble an ordinary payload, requiring perhaps an hour to arrive in range of its target. Once out of orbit, the FOBS would give only 3 minutes' warning, much less than the 30 minutes for ICBMs. Although the USAF has over-the-horizon radars which bounce high-frequency radio waves off the ionosphere and can thus detect FOBS in orbit, those radars can be affected by sunspot activity and are highly susceptible to jamming. Optical systems are much better suited for FOBS observations. (A probable scenario for FOBS weapons would be multiple launchings to take out many targets. Although a single FOBS would be difficult to identify, it would be strategically improbable that only one would be used, with the result that there might be even more warning time than for ICBMs.)[18]

Although the FOBS has been operational for many years, a different kind of space weapon, the Directed Energy Weapon (DEW), has been described more often in the press. The most heavily researched area of DEW development is that of the laser, and even it has received comparatively little funding: less than $2 billion has been spent by the Pentagon since the 1970's on high-energy laser weapons. However, the allocation for laser weapon research has been constantly rising.[19] The Soviet Union, too, has been pursuing DEW development. In fact one source has suggested that its laser weapons development programs are four or five times larger than those of the US, and that it presently has an operational low-altitude anti-satellite laser stationed at Sharyshgan.[20]

The potential for laser weapons is indeed enormous. A photon takes only six-millionths of a second to travel one mile, so that an ICBM travelling at Mach 6 at a range of 1600 km would travel only 3 metres during the flight of a laser beam towards it. But the situation is not quite so simple; a laser weapon (*at the present time*) cannot simply be pointed at incoming ICBMs and vaporize its targets. A certain length of time is required for the beam to burn through the outer shell of the target vehicle. Once through the shell, the beam must strike a vital component such as a guidance circuit in order to be effective. Also, during its passage through the atmosphere, a laser beam will diverge slightly and be dispersed by the atmosphere, so that the required "dwell time" on the target will be longer. Finally, the aiming and the disengaging mechanism must be extremely accurate in order to point the laser, distinguish targets, recognize when a target is disabled and move on to other targets.

Lasers can be defended against, at least to some degree. Cruise missiles, for example, are poor targets because of their erratic flight. The vital components of ICBMs can be shielded with highly reflective material, again increasing the required dwell time. Nevertheless, there is no question that the ideal medium for laser weapons is space because the atmospheric dis-

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[18] Brownlow, C. "Soviets Prepare Space Weapon for 1968", *Aviation Week and Space Technology*, 13 Nov. 1967, pp. 30-31.

[19] Primary source: Payne, K.B., ed., *Laser Weapons in Space*, Westview Press, Boulder, Colorado, 1983. Also: Canan, J. *op.cit.*, note 16.

[20] Main, Roger P. "The USSR and Laser Weaponry: A View from Outside", *Defence Systems Review*, V. 3, no. 3, 1985, pp. 67-80.

tortions of a beam in transit are removed. Lasers on a space-based platform could, therefore, be used to intercept ICBMs in flight.

The United States is currently developing DEW research through the Defense Advanced Research Projects Agency (DARPA) and its Space Defense Technology programs. Three main projects now underway are Talon Gold, ALPHA and LODE, all interrelated in the development of a space-based laser. In addition, the USAF has coupled a Hughes pointer-tracker with a laser aboard an Airborne Laser Laboratory (ALL). The ALL is very large and exceptionally manoeuverable, filling essentially the entire cargo bay of the plane. Both the Navy and the Army have laser programs as well, although their development has not achieved the "height" of the Air Force program.

The first practical laser came to light in 1960, when two American scientists developed the ruby laser which generated only one watt of power. The gas-dynamic laser was produced in 1967, giving 100 watts. Then, only a year later, a carbon dioxide laser was developed with an output of 60,000 watts. About this time, DARPA formed the High Energy Laser Research Group (HELRG) to study the use of lasers for weapons. Soon, the electric-discharge laser was developed, followed in the mid-1970's by the chemical laser capable of producing several megawatts.

A laser weapon was first successfully demonstrated in 1973 at the HELRG facilities at Kirtland AFB, New Mexico. A gas-dynamic laser, using a telescope to sight and point, shot down a drone aircraft, albeit a slow-moving one. Then, in 1978, a deuterium/fluoride laser shot down three TOW antitank missiles travelling at 500 mph. However, this required eight tries and a huge generating station to produce the needed 300-watt output. Nevertheless, the move to space seems only a short step away.

Particle beam DEWs, on the other hand, are not quite so far along in development. Their main advantage is that a beam need not "cut" through a missile, but only play upon its guidance circuits to be effective (although in actual operation, a beam would certainly raise the temperature of the missile).

As was true of lasers, there exist defences against particle beams, as well as problems in their operation. Any beam of particles (electrons, protons, neutrons, etc.) will tend to diverge because of the charges on the individual components, although neutron beams would be less susceptible to this. Furthermore, distortions in the geomagnetic field would wreak havoc with a beam, kinking and warping its path. In space, an Anti-ballistic Missile (ABM) DEW would need a radar-pointing system, which could be jammed or confused by chaff or decoys. Also possible is the detonation of a nuclear weapon in the atmosphere to disrupt a beam's propagation channels. It seems that, as with most weapons, an improvement in offence merely initiates an improvement in defence.

Despite these drawbacks, DARPA is currently operating the Particle Beam Technology Program, which has a directive to produce the required technology by 1987. One of its tasks is the "generation of low-divergence neutral beams for space applications". Clearly, this is the ASAT DEW system.[21] The USSR also seems to be engaged in research into particle beams for space weapons.[22]

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[21] Much has been written about the development of particle beam weapons. A very readable article is that by Parmentola, J. and Tsipis, K., "Particle Beam Weapons", *Scientific American*, V. 290, no. 4, 1979, pp. 54-65. It is excellent in its description of the technology and provides useful information on the weapon's weaknesses and vulnerabilities. The authors de-emphasize, however, the intense research devoted to the DEW development at the present time. While it is probably advisable to be cautious in discussions on DEW development, one must also recognize the advances of the past decade. Clearly, DEW weapons are edging closer to reality.

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[22] Main, R. *op cit.*, note 20.

Both the United States and Soviet Union have reusable space vehicles. The American Space Shuttle program is a major success despite its development problems. The Soviet Albatros (or Raketoplan) has also met with some success, although it is not widely publicized. Both vehicles can transport payloads into orbit and can intercept satellites for inspection. This last point is very important in terms of military value.[23]

Because of the delicate and fragile nature of a satellite payload, any deviation from 100% efficiency can be severely disrupting. Consequently, ASAT systems need not be very sophisticated: the simple collision with an "unarmed" ASAT missile would probably be sufficient.

Soviet ASAT technology is well ahead of any similar American effort. In 1976, the Soviets began a series of "killer satellite" tests employing target-seeking "oversized grenades" that could intercept a target in space. And, in 1981, the highly classified TEAL BLUE and TEAL AMBER tracking cameras (of the GEODSS advanced system) reportedly photographed ASAT launching tubes on Cosmos 1267 that docked with Salyut 6. This gave rise to the report that the Soviets were preparing to run an orbiting, anti-satellite "battle-station".[24]

The United States has been developing an ASAT capability in response to the Soviet system, but using a different technology. On January 21, 1984, an F-15 over the USAF Western Test Range launched an unarmed, two-stage Short-Range Attack Missile (SRAM) into space to test its guidance system.[25]

In all likelihood, despite these developments, the age of the space battle-station (the "Deathstar") is not *quite* upon us. Nevertheless, large ASAT bases are probably in the planning stages in both the US and the USSR. It is known, for example, that the Soviets are moving towards a permanent space station. It would be supported by the Progress unmanned "supply tug", reached with the new Soyuz-T manned vehicle, and may be an adaptation of the Cosmos 1267 "space station module".[26] It has been claimed that the "module" is nothing but a "cover-up" for a huge ASAT station. Telemetry from Cosmos 1267 is reported by the amateur Kettering group to be of a kind unmatched for other Cosmos flights.

Finally, there is the curious report that the Soviets have developed an immense particle-beam installation for defending against American ICBMs. According to USAF intelligence sources, a secret base has been built at Semipalatinsk in Kazakhstan. Deep underground is a large steel sphere connected to a magneto-hydrodynamic generator. Supposedly, a small nuclear device could be detonated in the sphere and the energy transferred through the generator into an accelerator where a proton beam would be produced. The physics of the system is not impossible, only beyond present capabilities. But the strategy in employing such a system appears skewed, since it is vulnerable to many countermeasures. Furthermore, a beam weapon with a "nuclear bomb" power source produces an unnecessarily strong proton stream according to critics (though perhaps the critics are overlooking the fact that a very powerful beam would carry several advantages over one produced more conventionally).[27] As mentioned earlier, although the placement of such a system on board a satellite is possible in theory, the satellite itself would be extremely vulnerable to ASAT weapons.

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[23] For details on the Soviet shuttle, see Covault, C. "Soviets Orbit Shuttle Vehicle", *Aviation Week and Space Technology*, 14 June, 1982, pp. 18-19. Also see Humble, R.A. "The Soviet Space Shuttle and Related Military Developments", *Canadian Defence Quarterly*, V. 12, no. 3, 1982/83, pp. 30-33.

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[24] Powell, J.W. "Photography of Orbiting Satellites", *Spaceflight*, V. 25, no. 2, 1983, pp. 82-83.

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[25] The ASAT test was noted in *Aviation Week and Space Technology*, 30 Jan., 1984, p. 19.

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[26] A good view on Soviet space development is that of Oberg, J. "Soviet Developments Point for Space Operations Center", *Astronautics and Aeronautics*, May 1982, pp. 74-77.

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[27] Douglas, J.H. and Thomsen, D.E. "The Great Russian 'Death-Beam' Flap", *Science News*, V. 111, 21 May, 1977, pp. 329-335.

Chapter Seven

Verification of Space Systems

There are several international agreements presently in force which directly and explicitly relate to the military use of space.[28] The first major agreement was signed in 1963. Usually called the *Partial Test Ban Treaty*, it prohibits the explosion of a nuclear device (*inter alia*) in outer space (Article I). There are currently about 111 parties to this treaty.

The placement of "nuclear weapons or other weapons of mass destruction" in Earth orbit is banned by the *Outer Space Treaty* of 1967. This important agreement also forbids "the establishment of military bases, installations and fortifications, the testing of any type of weapons and the conduct of military manoeuvers on celestial bodies." The *Outer Space Treaty* presently has about 92 parties.

The 1977 *Environmental Modification Convention* prohibits the hostile changing of natural processes, including those of outer space, which would result in widespread, long-lasting or severe effects (Articles I and II). About 54 states are presently parties to this agreement.

The above treaties are all multilateral agreements. One bilateral treaty between the US and the USSR also has direct relevance to outer space: the *Anti-ballistic Missile Treaty* of 1972. Under this agreement each party "undertakes not to develop, test or deploy ABM systems or components which are sea-based, air-based, *space-based*, or mobile land-based" (Article I, emphasis added).

Of course, although various treaties may be legally in effect, determining compliance with them is another matter. For example, the *Outer Space Treaty* is difficult to verify at the present time. It is possible that an unannounced, and hence unknown, nuclear weapon is in orbit at this very moment.

However, the use of GEODSS and other satellite inspection systems is slowly changing that situation. With ground-based optical systems, one can observe satellites in orbit and resolve details about them. As well, radiometers at GEODSS sites can detect radiative emission and/or leakage from orbiting satellites, checking power generation and their state of operation.[29]

Improved versions of GEODSS systems such as the TEAL AMBER sensor will be not only faster, but also more sensitive to faint objects in space. And new systems are continually being developed each year.

Ground-based observations have extended far beyond advanced astronomical systems. In the Middle East, a DARPA radar system is reportedly capable of actually forming images of low-altitude satellites.[30] The same is said of the MIT "Haystack" radar in Lexington, Massachusetts. At the Maui Optical Tracking and Identification Facility (MOTIF) in Hawaii, a lidar system (using light instead of radio waves) utilizes a "compensated imaging telescope" to maximize information received by analysis of its passive and active sensors.

Space-based reconnaissance systems are also used to observe satellites. Space-based systems first appeared in the 1960's for ground observation missions. When Eisenhower described the proposed "Open Skies" program, which was allegedly intended to provide verification without disarmament, the Soviets "curtly" turned it down. That was in 1955 at the Geneva Summit conference, only a year before U-2 spy planes began flying over Russia. Then, in 1960, with the U-2's out of action, Discoverer 13, the first "spy satellite", returned photographs of Earth.[31]

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[28] An excellent overview of arms in space and their relevance in arms control agreements is given by Lindsey, G.R. "The Military Uses of Outer Space and Arms Control", *Canadian Defence Quarterly*, V. 13, no. 1, 1983, pp. 9-14. For a detailed review of outer space law relevant to arms control see the Canadian working paper presented to the Conference on Disarmament entitled "Survey of International Law Relevant to Arms Control and Outer Space", CD/618, 23 July 1985.

[29] McNamara, F.L. and Krag, W.E., *op. cit.*, note 13.

[30] Karas, T. *op. cit.*, note 16.

[31] Steinberg, G.M. *Satellite Reconnaissance*, Praeger Publishers, N.Y., N.Y., 1983.

Since Discoverer, reconnaissance satellites have advanced enormously. In 1971, the first Big Bird satellite was launched. In its polar orbit, it sent television pictures back to Earth as well as film capsules. Big Bird flies at a perihelion of about 150 km, still higher than some smaller, "close-look" satellites sent up on speciality missions to examine a particular area of the globe.[32]

Of more strategic importance than the Big Bird series of satellites is a highly secret series called the KH-11. The first of these was launched in 1978, and has a higher perihelion (about 250 km), and hence a longer lifetime, than the Big Birds. KH-11's have GEODSS-type electro-optical sensors on board, for the extreme resolution of ground stations. It is believed that KH-11's also probably have sophisticated infrared sensors for "observing" underground missile bases. Big Birds can release data packages to be picked up in nets trailed by aircraft. KH-11's, on the other hand, transmit their data to ground stations such as those at Thule or Guam, or else to higher-orbiting Defense Support Program (DSP) satellites for processing and later transmission.[33]

In addition, there exist Rhyolite VHF ELINT satellites for monitoring communications, and Vela Hotel satellites for monitoring radioactive emissions.

Satellite-to-satellite viewing may already have been employed. When the first space shuttle lost some tiles during its launch, not only were GEODSS sites used to examine its heat shield in detail, but Big Birds and/or KH-11's examined it from orbit as well.[34] It is reasonable to assume, therefore, that observations of other satellites could be made routinely by systems such as the KH-11's.

The idea of using satellites to verify satellite activities is not new. For example, the United States created Satellite Inspection (SAINT) interceptors as early as 1960. The purpose of the SAINT program was twofold: 1) satellite inspection of other satellites by satellites at close range, and 2) actual interception of satellites by satellites. This first practical ASAT system was phased out for various reasons, one of which was the possibility of "enemy" satellites being "booby-trapped" to prevent close inspection. Also, inspection by one side would certainly encourage inspection by the other, and this might not be desirable.

(With regard to "booby-trapped" satellites, consideration might be given to Salyut 6, which apparently possesses ASAT "missile tubes". The one-metre tubes were unusually small for an offensive ASAT system, but were regarded as experimental. However, the subject of "space mines" has been mentioned in ASAT literature, and the possibility that the tubes are mine launchers for *defensive* action must be acknowledged.)[35]

Since existing satellite reconnaissance systems are designed to inspect sensitive areas both on the ground and in space, and because they are in generally low orbits, they are prime targets for ASAT devices. One only has to remember the U-2 incident to realize the precarious situation of reconnaissance missions. With the development of ASAT weapons, a space-based repeat of that incident is possible. In fact, it may have already occurred: it was suspected that a ground-based Soviet laser was responsible for the "blinding" of an American reconnaissance satellite, although later reports "identified" the cause as gas fires in the Persian Gulf.[36]

In the future, since ground-based radar is limited to low-orbiting satellites and GEODSS is limited to night-time, clear-sky viewing, an entirely new system may be required. This system may consist of inter-orbital optical systems, based in space, and ground-based lidars.

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[32] Karas, T. *op. cit.*, note 16.

[33] *Ibid.*

[34] Hoagland, R.C. "Superspy in Orbit", *Science Digest*, V. 89, no. 6, July 1981, p. 32.

[35] Oberg, J. "Soviet Developments Point for Space Operations Center", *Astronautics and Aeronautics*, May 1982, pp. 74-77.

[36] Main, R. *op. cit.*, note 20.

Chapter Eight

Summary

Arms races and military competition can lead to highly destabilizing and dangerous situations. Strategic stability can, however, be improved by the introduction of arms control treaties with effective verification procedures. It is towards this goal that any reasonable proposals must lead.

Astronomical techniques show promise for their use in verification strategies for space-based weapons systems. Since the launching of the first satellites in the late 1950's, their observation and tracking have been a high priority for military defence. These tasks were first performed under the auspices of the civilian MOONWATCH program, then hurriedly updated to Baker-Nunn photographic camera sites. As soon as these were in operation, it was obvious that they were still unsatisfactory because of their non-real-time nature.

Photometric observations were the next to be tested, with the technology borrowed directly from astronomy. Eventually, on-line electro-optical systems were developed that improved both resolution and the capability of real-time requirements. Throughout the development of sensors for tracking purposes, the instruments and technology used have been primarily astronomical in nature. A point has been reached now, however, where military astronomy technology has surpassed civilian astronomy technology. GEODSS sites, in fact, have been petitioned by astronomers to install "black boxes" to store stellar data for later transfer to laser disks and distribution to astronomical institutions. Asteroid surveys have also been performed with GEODSS equipment with some success.

Optical satellite surveillance is an extremely crucial element of the NORAD SPACETRACK system. In addition to the civilian telecommunications' need to maintain an accurate record of satellites, there is a very real need for military tracking. Since radar is accurate only to about 5,000 kilometres in altitude, optical systems are needed for high-orbit satellites. GEODSS thus fills a gap in surveillance systems. The TEAL AMBER sensor and its future generations will improve resolution greatly over the next decade, and the use of active systems, such as lidar satellite tracking, may supplement observations to a larger extent.

Satellite tracking is becoming more important at the present time as the implications of ASAT systems become better understood. Observations of satellite manoeuvers can lead to information on the operation of military missions in space. These observations can be used by verification groups to assess the extent to which space is becoming militarized.

The concept of the verification of space systems is worthy of pursuit, but another set of procedures must be developed for ground-based sensors. From a purely astronomical standpoint, the suggestion that GEODSS sites turn over stellar data is an interesting one. But a satellite verification group could make use of tracking data as well. An independent group could analyze the tracking data for unusual or unwarranted space activity. This is providing, of course, that the information is releasable. If not, since the technology is available, then independent GEODSS sensors could be built.

The Baker-Nunn camera at Cold Lake, Alberta, which was removed from service because of its non-real-time capability, was given to the University of Calgary for astronomical use. If other existing Baker-Nunn systems were replaced by electro-optical systems with a near-real-time capability Baker-Nunn cameras might then be made available to astronomical institutions and/or reserved for possible future use by verification groups.

Not to be excluded from consideration is a possible catalog of satellite-to-satellite observations. If a verification group was granted even partial access to such a catalog for the purposes of the verification of satellite intent and inspection, the arms control features would be valuable indeed. If these data were to be made available bilaterally, then the effect would be inherently stabilizing.

Many arms control verification proposals involving satellite reconnaissance and other types of space systems have been made during the course of arms talks. These have ranged from the use of satellite reconnaissance to detect the construction of missile bases to the actual on-site inspection of launch platforms. This shows exactly how valuable space systems are for the prospects of arms control.

Chapter Nine

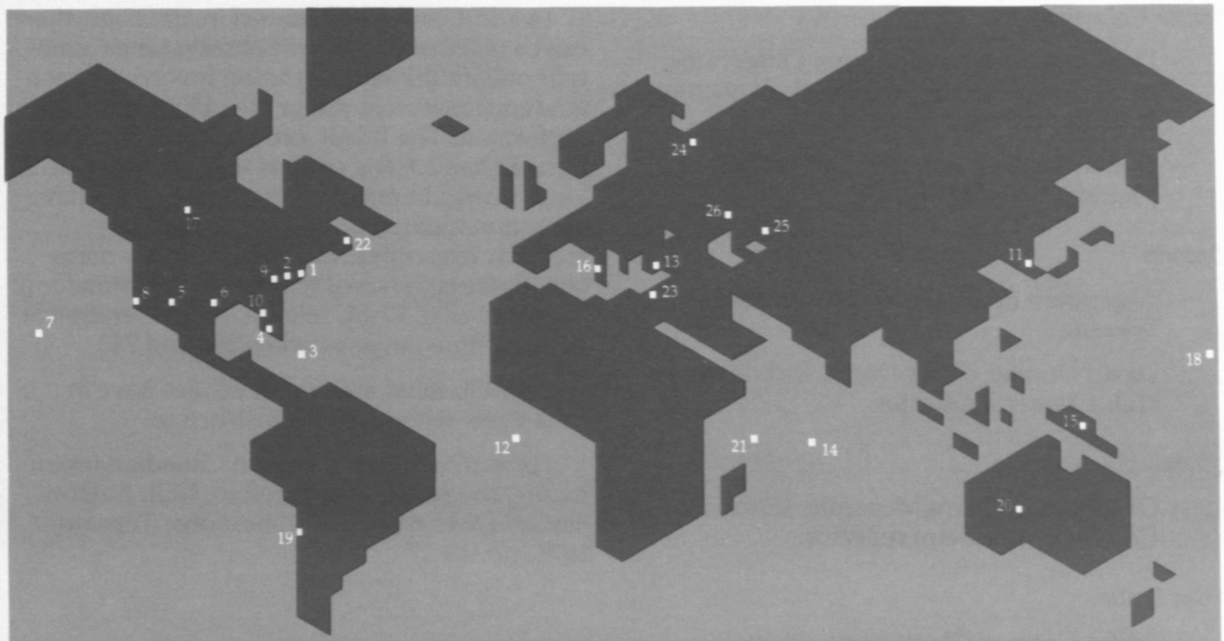
Canada and Ground-Based Systems for Space Verification

At this moment, there is one electro-optical satellite tracking station in Canada, namely the St. Margaret's site in New Brunswick. Although not a true GEODSS site, it has many of the GEODSS functions, and its data are used to update the NORAD satellite catalog. While there are several GEODSS stations around the world, the ability of some satellites to change orbits rapidly for offensive manoeuvers might suggest that additional stations could be welcomed to provide accurate, real-time tracking. At least one additional GEODSS or GEODSS-clone station might be installed in Canada. The location would be dependent on the preference for a maximized number of hours of clear skies to facilitate optical tracking. The areas in the country with the highest average number of hours of clear skies yearly are the Prairies, particularly the southernmost parts of Alberta, Saskatchewan and Manitoba. Those areas have as much as 25% more hours of clear skies than New Brunswick. Perhaps the Cold Lake site could be upgraded, though a more southerly location might be better. Another alternative, given the possibility of over-the-pole activities, is a location in the Northwest Territories. Considering, however, that many satellites have orbits taking them over the Eastern Seaboard, an additional eastern location could be proposed, although the St. Margaret's site could easily handle the traffic if upgraded. In any instance, if additional GEODSS systems are installed the burden on existing sites would be eased and the accuracy of the data received would be increased.

Satellite verification proposals might be expanded to include GEODSS, radar, lidar and other tracking systems. Soon, one satellite system may be able to detect individual aircraft from space. Its ability to locate airborne ASAT flights would certainly further stabilize the space-based arms control situation. Such information would be invaluable to verification systems as well.

Arms control verification goes to the heart of any ACD agreement because it addresses both compliance and confidence. In terms of the outer space issue it is clear that new types of multilateral verification should be critically examined. This study recognizes that the application of ground-based remote sensing techniques to the problem of arms control verification in space does not constitute a viable system in and of itself. It will be an effective component, however, of an integrated system. Canada appears to be well positioned to make significant contributions to discussions on verification in outer space. It has the technical means and expertise to design and operate a space-based verification system. It has, as well, a considerable capacity to contribute to ground-based verification studies on an international scale and possesses the necessary technical means, manpower and facilities to remain in such a position for long-term goals. Astronomy is one of Canada's prized scientific strengths. It could be mobilized to contribute both conceptually and practically to verification research associated with outer space. Much will depend upon the likelihood of significant outer space treaties agreed to by nations having considerable assets in space and a determination of how far Canada should proceed with others in developing a verification capability given the rapid evolution of space utilization.

Appendix 1: Satellite Tracking Sites in the GEODSS File



Map Key

1. Milstone Hill, Maryland, U.S.A.
2. Haystack Observatory, Maryland, U.S.A.
3. Arecibo Radio Observatory, Puerto Rico
4. Elgin AFB, Florida, U.S.A.
5. Lincoln Experimental Test Site, New Mexico, U.S.A.
6. Shemya, Arkansas, U.S.A.
7. GEODSS, Hawaii, U.S.A.
8. Edwards AFB, California, U.S.A.
9. Navapasur, Virginia, U.S.A.
10. Patrick AFB, Florida, U.S.A.
11. GEODSS, South Korea
12. GEODSS, Ascension Islands
13. Diyarbikar, Turkey
14. Diego Garcia (Island)
15. Mount John, New Zealand
16. San Vito, Italy
17. Cold Lake, Alberta, Canada
18. Kwajalein Atoll, Marshall Islands
19. Cerro Tololo Observatory, Chile
20. Northwest Caper, Australia
21. Seychelles Islands
22. St. Margaret's, New Brunswick, Canada
23. Negev Desert, Israel
24. Plesetsk, U.S.S.R.
25. Tyuratam, U.S.S.R.
26. Kapustin Yar, U.S.S.R.

Appendix 2 : Major Canadian Astronomical Institutions

British Columbia

- Dominion Radio Astronomy Observatory, National Research Council, Penticton; 26-metre reflector.
- Dominion Astrophysical Observatory, Victoria; 1.75-metre reflector.

Ontario

- Algonquin Radio Observatory, Lake Traverse.
- David Dunlap Observatory, Richmond Hill; 1.8-metre reflector.

Quebec

- Observatoire Mont Megantic, Comt Compton; 1.6-metre reflector.

Nova Scotia

- Burke-Gaffney Observatory, Halifax.

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In addition to professional institutions, there exist a number of amateur observatories, amateur only in the sense of being involved in non-academic research, not in the quality of work performed. The Royal Astronomical Society of Canada has 2,600 members nationwide, with 20 local centres in major cities. Most centres have operational observatories with small-to-medium telescopes. In addition, many members possess personal instruments. Estimates of the number of RASC telescopes in operation at any one time range between 500 and 750.

As well, most major universities have at least a few telescopes for instruction.

For further information on Canadian instruments, the reader is referred to: Gall, J. *Astronomical Directory*, Gall Publications, Toronto, 1978, pp. 13-17.

Arms Control Verification Studies

No. 1 *A Conceptual Working Paper on Arms Control Verification*, by F.R. Clemenson and E. Gilman, January 1986

Canada