CHAPTER 8

VERIFICATION MODELS FOR SPACE WEAPONS TREATIES: A FLEXIBLE, LAYERED APPROACH AS A NEGOTIATING TOOL

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INTRODUCTION

The purpose of verification is to increase confidence in the implementation of a treaty. An effective verification system reliably detects non-compliance and allows abiding states to credibly demonstrate their compliance. It can also deter non-compliance, depending on the strength of enforcement measures within the treaty. Verification is necessary for an effective treaty in that it provides an objective trigger for enforcement measures and legitimizes those measures when they are implemented.

In the context of space security, official multilateral treaty verification is necessary for three further reasons. The first is the hazardous nature of the space environment. There are natural and man-made threats to satellites and spacecraft that can cause temporary or permanent damage, including solar radiation and orbital debris. Without a verification system it is difficult to credibly distinguish between natural causes of satellite failure and the effects of weapons use. The second reason emerges from dual-use problems of space verification technology: unilateral monitoring activities by individual states may be interpreted as offensive in nature and potentially provoke a protection-negation arms race. For example, a close-proximity fly-by to inspect a satellite could easily be interpreted as an interception attempt or surveillance for military advantage. The only way to engage in such sensitive activities in a non-provocative manner is to do so multilaterally. And third, there are many dozens of state and commercial actors with space assets, yet current capabilities for knowing what is happening in space are limited to only a handful of states. This means that verification of any allegations of illicit space weapon deployment or use is

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at the moment dependent upon the national technical means (NTM) of a select few.

Verification of a space weapons ban is technically possible. It may also not be as expensive as some analysts have suggested if it can leverage existing and emerging technologies and exploit synergies between verification methods. The primary determining factors for the design of a verification system are the scope of the treaty being negotiated, the level of confidence deemed necessary to assure compliance (for example, guaranteed 100% detection versus 60% certainty) and the level of intrusiveness politically palatable to negotiators (for example, limited versus anytime, anywhere on-site inspections). The last two factors are subjective and dependent on the larger international political environment and, therefore, each country must determine for itself what level of confidence and intrusiveness it desires and how such levels will influence the effectiveness of its desired treaty design. Answers to these questions will then help determine the acceptable level of cost.

Verification has been left out of some proposals for space weapons treaties due to its perceived complexity and divergent views about its effectiveness. To assist in negotiation and decision making, however, verification measures related to proposed treaty elements can and should be described ahead of time. This paper attempts to outline an encompassing framework, to be strengthened with further research, which can be flexibly applied to varying treaty requirements (see Table 1). For each potential treaty design there can be multiple layers of verification, allowing negotiators to balance cost, intrusiveness and effectiveness to provide the optimum level of confidence possible within the current context. The framework also highlights potential synergies between verification methods to increase confidence and cost-effectiveness.

WEAPON CATEGORIES: EARTH-TO-SPACE, SPACE-TO-SPACE AND SPACE-TO-EARTH

There are three categories of weapons that can be addressed in a space weapons treaty: weapons on Earth that target space assets (Earth-to-space); weapons deployed in space that target other space assets (space-to-space); and weapons deployed in space that target assets on Earth (space-to-Earth). Each category offers unique challenges and opportunities for verification.

An Earth-to-space weapon is fired from the ground, sea or air. For example, a ground-based laser can be used to damage satellites, or an anti-satellite (ASAT) interceptor can be launched from an aircraft. One challenge for verification is the dual-use nature of many Earth-based weapons. Licit weapons designed to attack ground or air targets, such as ballistic missiles and high-powered lasers, could potentially target space assets. They can, thus, be difficult to detect as ASAT weapons until they are used or tested against space targets. On the positive side, if Earth-based facilities are declared, continuous on-site monitoring on the ground is much easier than monitoring in space.

Space-to-space weapons are placed into orbit to target other space objects. Examples include space mines, lasers and interceptors. Space-to-Earth weapons are still mostly theoretical, but could include things such as orbital bombardment systems, space-based ballistic missile interceptors or space-based lasers. Deployment of weapons into space (both space-to-space and space-to-Earth) faces the choke point of launch into orbit. This offers a valuable opportunity for verification that is not available for Earth-to-space weapons. Objects in orbit are also difficult to hide, a fundamental advantage in detection over Earth-based weapons. Dual-use technologies also exist related to objects deployed into space, such as on-orbit servicing spacecraft, and pose a challenge similar to Earth-to-space dual-use technologies.

PROCESS STEPS: RESEARCH, TESTING, DEPLOYMENT AND USE

The process of creating a space weapon can be divided into four steps: research and development, testing, deployment, and use.[1]

RESEARCH AND DEVELOPMENT

A ban on research and development of space weapons or weapons to target space would prove difficult to verify, and likely be unpalatable to states. It would require intrusive inspections of laboratories and development facilities, and a very high degree of cooperation. Hidden or clandestine laboratories would prove difficult to detect and identify, and the line demarcating the parameters of acceptable research would be hard to define.

TESTING

Laboratory testing of space weapons is limited in its reliability. Complete confidence in a space weapon's capability will invariably require testing of the complete prototype in the field (that is, space) and, therefore, field testing acts as a verification choke point between development and deployment. The methods for verifying field testing against space targets are the same as for verifying use, though greater sensitivity is needed in order to detect tests done at lower power or without explosives or other weapons functions. Verifying the testing of individual components of space weapons is more difficult, as they can often have non-weapon uses or can be tested in laboratory conditions. Some technologies are almost completely dual use as the final product can be used for weapon and non-weapon purposes (for example, micro-satellite rendezvous and space tugs). Verifying testing, thus, faces many of the same dual-use confidence problems as verification of deployment, and would require use verification to fill the confidence gap.

DEPLOYMENT

Verifying deployment of weapons into space is potentially one of the easiest verification activities, but has significant limits. The number of launches each year and the number of launch sites around the world are limited, presenting a significant verification choke point. Pre-launch payload inspections would, thus, be a valuable tool, and launch detection could flag any undeclared launches. The gap is in the dual-use nature of many satellite technologies. When a satellite can be changed into a weapon simply by ramming it into another satellite, deployment verification clearly is not adequate to cover all possibilities. Verifying deployment of Earth-to-space weapons faces different challenges due to the ability to hide weapons from detection. It would be extremely difficult, for example, to verify that there are no ASAT interceptors under the wings of any aircraft in all the hangers around the world. Larger facilities such as high-powered lasers, on the other hand, could be more easily detected and monitored.

USE

Verifying a ban on weapon use is an essential stopgap measure of last resort. It does not provide any early warning and would leave the door open to significant "break-out",[2] yet, as discussed above, the dual-use nature of many space and weapon technologies sometimes rules out any other type of verification. It is also essential for assigning responsibility for satellite failures and distinguishing between weapon use and natural causes. Verifying use is limited only by the ability to detect an attack, which is significant given the necessary technical capabilities and costs involved in maintaining a detailed awareness of space activities.

METHODS OF VERIFICATION

Verification methods for future space weapons treaties can be structured in six layers: on-site verification; launch detection and post-launch confirmation; space situational awareness; on-orbit inspection; detecting the use of laser and other directed energy weapons (against space targets or from space against Earth targets); and re-entry detection and characterization.

ON-SITE VERIFICATION

Two variations of on-site verification could be employed: continuous on-site monitoring and on-site inspections. Both involve significant degrees of intrusiveness, and as such require sufficient political acceptance. Continuous on-site monitoring involves the permanent stationing of equipment and/or personnel at launch sites or other designated facilities. On-site inspections would entail the presence of inspectors at designated sites for limited periods. The level of intrusiveness for pre-launch inspection could amount to no more than a cursory inspection of spacecraft exteriors prior to final encapsulation. Inspections of payloads and facilities, the gathering of information on vehicle fuel capacity, flight and orbital paths and other data required to confirm a satellite's function would be far more effective, but would also necessitate greater openness by the host state. Concerns about the protection of sensitive commercial or security-related information can be mitigated with confidential data management policies and managed access techniques similar to those practised by inspection teams of the Organisation for the Prohibition of Chemical Weapons and the International Atomic Energy Agency (IAEA). If such concerns can be addressed to the satisfaction of states parties, on-site verification would be a useful and low-cost component of a space weapon verification system.

LAUNCH DETECTION AND POST-LAUNCH CONFIRMATION

Verifying launches, particularly those that are undeclared, would be a key component in any verification system for a space weapons treaty. This verification method can be achieved in a number of ways with current technologies. Allegations of an undeclared launch could be confirmed or discounted by a post-launch on-site environmental sampling. Undeclared launches could be detected by use of infrasound and hydroacoustic sensors similar to those currently employed by the International Monitoring System (IMS) of the Preparatory Commission of the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO).[3] These sensors detect sound waves travelling through the oceans and atmosphere, and would be a cost-effective way to verify sea and airborne launches in areas that may be difficult to reach with radar.[4]

An array of ground-based radars would provide very reliable launch detection, capable of surveillance, acquisition, tracking and discrimination. It could detect ballistic missiles, space vehicle launches and ground and air-launched kinetic-kill ASATs.[5] Over-the-horizon and sea-based radars could extend coverage into areas difficult to reach with standard ground radars. The most expensive option, but one providing the greatest global coverage, is the use of infrared monitoring satellites to detect rocket plumes in launch and boost phases.[6] Few states currently possess such capabilities, as the costs involved in acquiring and deploying infrared monitoring satellites are considerable. One satellite alone, however, could cover a third of the Earth and fill any gaps that exist in the coverage of other launch detection methods.

SPACE SITUATIONAL AWARENESS

Space situational awareness (SSA) is the general term referring to all monitoring of activity in space. This is the only verification method capable of detecting the use of many space weapons. SSA solves the dual-use dilemma by verifying the use itself. It tends to be prohibitively expensive, however, with the cost of many systems running into the hundreds of millions of dollars. Ground-based SSA is carried out using two types of technology: radars and optical telescopes.[7] Ground-based radars and telescopes are currently the most reliable method for tracking known objects, searching for new objects and characterizing objects.[8] An emerging solution is to put radars and telescopes into orbit. This overcomes several limitations of ground-based SSA, but is usually more expensive.[9] A further option is to place limited SSA capabilities on new satellites as a protective feature, focused on proximity awareness around the satellite.[10] Mandatory placement of standardized locator beacons on satellites (especially those with dual-use functions) could also improve monitoring efforts.[11]

On-orbit inspection

The concept of on-orbit inspection is quite simple: it involves sending a satellite with cameras and other sensing devices to inspect another satellite in space. Such an inspection would be a last resort, useful only if other verification measures such as payload inspection or launch detection were circumvented or not sufficient to determine compliance or non-compliance. An inspection could involve a quick fly-by or a more lengthy rendezvous and fly-around. Proposals for inspection satellites were first advanced in the 1980s, and feasibility studies at the time specified requirements involving satellites of over four metric tons and costing in the hundreds of millions of dollars.[12] Technology has progressed rapidly since then, especially in the area of micro-satellites and nano-satellites. The precise size, weight and cost of the satellite will depend on the number of sensors on-board[13] as well as the number and type of missions it will be designed to carry out, though it is now possible to outfit a small satellite weighing less than 10kg with an array of optical cameras to fly by and photograph other satellites, and do so for less than US$ 2 million.[14] Launching satellites into orbit is also getting cheaper, with some commercial services offering launches of 600kg payloads into low-Earth orbit (LEO) for as low as US$ 7 million.[15] Launch capabilities are also becoming more responsive, with launches requiring less time to plan and execute.[16] On-orbit inspection is, thus, far more feasible today than when first proposed.

Detecting use of laser or directed energy ASATs

Detecting the use of lasers and other directed energy weapons is one of the most technically difficult verification activities. The only completely reliable way to detect laser attacks against satellites is through sensors on-board the target satellites themselves. Many military satellites already have such sensors and, though they add weight, they could be included on all new satellites to provide confirmation of the power and incident direction of a laser or directed energy beam. Other methods for verifying laser use include detecting radiation scattering as a laser passes through the atmosphere, detecting the laser's heat signature when in use, detecting light reflected off the target satellite and monitoring targets for unique types of damage.[17] Knowing a ground-based laser's location allows placement of sensors nearby to better detect atmospheric effects. Airborne lasers are far more difficult to monitor as they limit detection of atmospheric effects and increase the potential number of satellite targets. Airborne or space-based mirrors further complicate verification, as these would allow targeting of satellites beyond line of site and permit greater beam travel outside the atmosphere.[18]

RE-ENTRY DETECTION AND CHARACTERIZATION

The detection of objects re-entering the atmosphere has not yet been extensively explored for verification purposes, but it has important applications in detecting space-based weapons targeting Earth with physical objects. Research related to meteoroid collisions with the Earth's atmosphere has demonstrated cheap methods for accurately detecting and characterizing trajectories of high-speed re-entry objects. Radio frequencies are reflected by the plumes of ionized air behind an object's path, detectable with simple antennae.[19] Explosions, such as those created by bolides[20] when they strike the atmosphere, can be detected with infrasound techniques similar to those used by the CTBTO's IMS.[21] A network of such detectors could verify the occurrence and location of a re-entry event and potentially determine characteristics such as energy and velocity. Infrared monitoring by satellite, though more expensive, could also track re-entry events.

COSTS

SYNERGIES

One benefit of the layered approach to verification is that it allows verification methods to supplement each other to increase both cost-effectiveness and confidence levels. Even limited pre-launch payload inspections, for example, can limit the number of satellites that need to be monitored once in orbit. A mix of verification methods can be chosen to exploit these synergies, narrow confidence gaps and minimize costs.

PIGGYBACKING

Establishing agreements to employ existing systems and assets may also mitigate costs. A treaty verification system could, for instance, utilize the NTM of individual states to reduce capital outlay and increase effectiveness. Concerns regarding the reliability of NTM-derived data employed within a multilateral agreement would, of course, have to be addressed, but given that some systems such as high-powered radars have cost into the hundreds of millions of dollars, such cooperation may be necessary. Multilateral technical means that are already operational may also be an option. The CTBTO already operates global infrasound and hydroacoustic networks, and it has already considered data provision for purposes outside the CTBT mandate such as tsunami warning systems and monitoring volcanic activity.[22] If a space weapons treaty could be developed, perhaps states parties to the CTBTO would allow it to sell data to a space weapons treaty verification body.

COST-FIRST DETERMINATION

When assessing costs, a useful exercise would be to start with a set budget and see what verification system could be built. The exact mix of verification methods could be manipulated to demonstrate the maximum level of confidence achievable for US$ 50 million, US$ 100 million, US$ 150 million and so on, providing an even more concrete tool for negotiators. Further research is needed to describe the precise costs and options within each verification method.

CONFIDENTIALITY AND DATA MANAGEMENT

Securing proprietary commercial information and information pertaining to national security will be critical to establishing an effective verification system. Commercial and state actors would call for guarantees that all sensitive information gathered by a verification system will not be revealed to outside parties. A strategy to protect information need not reinvent the wheel, but can be modelled on similar existing arrangements. The United Nations Monitoring, Verification and Inspection Commission, in partnership with the IAEA, has already demonstrated that information and data can be collected, including NTM, while successfully protecting confidentiality.[23] On-site inspectors and staff supporting a verification system would be required to respect strict rules of confidentiality, and be legally bound to do so.

The management of raw space surveillance data is related to confidentiality, and will determine the ability of the verification system to contribute to extra-treaty benefits such as space traffic control or orbital debris tracking. The CTBTO model, which allows state signatories access to raw monitoring data almost in real time, may not be workable for a space weapons treaty, given national security concerns and legitimate military uses of outer space. Moreover, providing space surveillance data to commercial and other non-state actors with significant space assets will prove problematic as they will not be parties to the agreement. Questions arise as to whether data streams would filter military space traffic in ways different than civilian space traffic. These concerns must be addressed in treaty negotiations, which would set any such parameters for a verification data management body.

CONCLUSION

A clear understanding of verification possibilities and costs will greatly facilitate the negotiation of a space weapons ban. Countries proposing draft treaties should, therefore, try to consider the precise verification methods applicable to the treaty design envisaged. Effective multilateral verification can legitimize enforcement mechanisms and increase the effectiveness of the treaty as a whole.

Clear ideas on the verification measures required may force negotiators to be more specific about the treaty's terms and scope. While many contend that treaty objectives must be established in advance of any detailed discussion on verification, one can credibly counter that knowing which tools are technically available, financially feasible and credibly effective could help to initiate or shape treaty negotiations.

The verification system applicable to an agreed upon space weapons treaty could also provide a number of extra-treaty benefits. Such a system could play an effective role in helping avoid collisions in space by coupling SSA with a space traffic management system. It could also track space debris, a threat to all space assets that continues to grow.[24] An effective verification system could also reinforce compliance with the current registration and liability conventions.

The flexible, layered framework proposed in this paper will hopefully serve to catalyse a deeper formulation of verification plans for a space weapons treaty. Yet, depth must not create unnecessary complexity. Simple, policy-relevant considerations related to cost, intrusiveness and confidence levels are essential. Developing a comprehensive and flexible verification blueprint could serve well the needs of treaty negotiators in advance of agreement on treaty objectives, and provide impetus to future discussions.

Table 1. Treaty requirements and corresponding verification mechanisms

Treaty scope	Verification mechanisms
Banning use of weapons against space assets or from space against Earth targets	**Declarations and pre-launch payload inspections** would increase confidence and decrease costs of verification, but inspections would only verify deployment/non-deployment, not use
	Detection of undeclared launches Increased need due to ground- and air-launched kinetic ASATs Confirmation of launch by post-launch on-site inspection Infrasound and hydroacoustics Ground-based detection radars Infrared monitoring satellites
	SSA LEO orbit tracking and un-cued searching with a ground-based radar fence Ground-based optical telescopes for characterizing assets in LEO and tracking and characterization in GEO High-power ground-based radar and highly sensitive receivers for tracking, un-cued searching and characterizing in GEO Space-based SSA through radar satellites and space-based telescopes Locator beacons on satellites to facilitate tracking On-board SSA on each satellite (radar/lidar)
	Laser ASAT detection *Ground-based lasers* Sensors near declared laser sites to detect use, verify target and power *Airborne lasers* Radar systems to track location of airborne lasers *Both* Ground-based monitoring of potential target satellites for reflection of laser light Detectors on board satellites Satellites monitoring the atmosphere for laser effects
	Re-entry detection and characterization Radio reflection monitoring similar to meteorite detection Infrasound Radar tracking Infrared-monitoring satellites

[*] Cost levels are defined as follows: Very low = less than US$ 10 million;
Low = US$ 10–50 million; Medium = $US 50–100 million;

Setup/ infrastructure costs*	Operational costs* (per year)	Confidence gaps
Low	Low	Air launches
Low[25]/Med[26]	Low/Med	Assuring global coverage
Med/High	Low	Detecting trajectory
Very high[27]	Low/Med	Assuring global coverage
High[28]	Low	No coverage of GEO
High[29]	Low/Med	Limited un-cued searching in GEO
Very high[30]	Low/Med	Resolution still limited
Very high[31]	Med	Very high confidence
Low/Med	Low	Not present on all satellites
Med	Low/Med	Little warning time
Low	Low	Undeclared sites
Med/High[32]	Low	Global coverage
Med	Low	Complete coverage of all targets
Med	Low	Not present on all satellites
Very high	Low/Med[33]	Difficult to detect from a distance, depending on laser energy
Low	Low	
Low	Low	
Med/High	Med	
Very high	Low/Med	

High = US$ 100–500 million; Very high = greater than US$ 500 million.

Table 1 (continued)

Treaty scope	**Verification mechanisms**
Banning *deployment* of weapons in space	**State and commercial declarations of upcoming launches and detailed mission plan** Central depository and tracking database
	Pre-launch on-site verification of satellite payloads (continuous on-site monitoring and on-site inspections) Cursory inspection of spacecraft and payload exteriors prior to final encapsulation; general description of mission goals Visual interior and exterior inspection at selected stages; presence at selected tests and real-time review Complete access to technical data; visual inspection at any time; presence at all tests Disclosure of all technical data submitted in advance; unlimited visual inspection, including unit/panel removal; radiographic examination where possible; 24-hour surveillance
	Detection of undeclared launches (see above)
	SSA (see above)
	On-orbit inspection and surveillance Fly-by with inspection satellite On-orbit rendezvous for intensive inspection
Banning *testing* of weapons for placement in or for targeting space	**Verifying field testing of full prototypes** Generally requires the same technology as detecting use (see above) **Verifying testing of component parts** Laboratory inspections
Banning applied *R&D* of weapons to be used in space or to target space assets	**Verifying in-laboratory testing** Laboratory inspections

Setup/ infrastructure costs*	Operational costs* (per year)	Confidence gaps
Very low	Very low	No verification; very low confidence
Low	Low	Undeclared launches; dual-use technologies; hidden or opaque payloads; false data provision; limited intrusiveness
Med[34] Med/High[35]	Low/Med[36] Low/Med[37]	Small or hidden weapons
Low	Low	Easily hidden; dual-use problems
Low	Low	Laboratories are easily concealed; dual-use problems are enormous

Notes

[1] Production is often included as a potential step. Regulating production can involve setting limits on weapon capabilities or on the number of weapons to be produced. Tracking production of dual-use technologies could also be a potential flag, but requires very high levels of intrusiveness.

[2] "Breakout" here refers to a state building up its capabilities and arsenals to a high level without breaking the treaty, providing a military advantage that can then be quickly exploited when it does break the treaty.

[3] *Monitoring Technologies: Infrasound*, Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, 2006, at <www.ctbto.org/verification/infrasound.html>.

[4] *Monitoring technologies: Hydroacoustics*, Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, 2006, at<www.ctbto.org/verification/hydroacoustics.html>.

[5] *Ground-Based Radar and X-band Radar*, Federation of American Scientists Space Policy Project, July 1999, at <www.fas.org/spp/starwars/program/gbr.htm>.

[6] Simon Collard-Wexler et al., 2005, *Space Systems Protection*, Waterloo, ON, Space Security 2004, Spacesecurity.org, pp.103–104, at <www.spacesecurity.org/SSI2004.pdf>.

[7] SSA can also include ground-based infrared monitoring of satellites. For example, see Major Michael J. Muolo, 1993, Space Support to the War Fighters: Space Missions and Military Space Systems, Chapter 3, in *Space Handbook: A War Fighter's Guide to Space,* Maxwell Air Force Base, AL, Air University Press, December, at <www.au.af.mil/au/awc/awcgate/au-18/au180001.htm>.

[8] See Tim Grayson, *Space Situational Awareness: What was that? Where is it going? What is it doing?*, presentation at the DARPA Tech 2002 Symposium, Anaheim, CA, 30 July–2 August 2002, at <www.darpa.mil/DARPATech2002/presentations/tto_pdf/speeches/GRAYSON.pdf>.

[9] The United States is exploring this option with its Space-Based Surveillance System currently under development. See Simon Collard-Wexler et al., op. cit., pp. 125–126. For a complete list of past, current and planned space-based telescopes, see <www.seds.org/~spider/oaos/oaos.html>.

[10] Such on-board situational awareness is planned for the upcoming Orbital Express mission, see Lt. Col. James Shoemaker, *Orbital Express Space Operations Architecture*, US Defense Advanced Research Projects Agency, at <www.darpa.mil/tto/programs/oe.html>. It is also being explored by the United States Air Force in the form of Autonomous Nanosatellite Guardians for Evaluating Local Space (ANGELS), at <fs2.fbo.gov/EPSData/USAF/Synopses/2682/BAA-VS-06-03/BAASolicitationforANGELS%28Final2Dec05%29%2Edoc>.

[11] Tracking of satellite beacon signals using radio receivers is a common method for amateur astronomers, see S. Solomon, 1984, Eavesdropping on Soviet Satellites, *Science Digest*, vol. 92, no. 1 (January), pp. 26, 32, 81. The method is also used by the United States Deep Space Tracking System, see *5th Space Surveillance Squadron: Factsheet*, United States Air Force, 2005, at <www.peterson.af.mil/21sw/library/fact_sheets/5spss.htm>; and was proposed in a 2004 US study on guidelines for re-usable launch vehicles, see J. Timothy Middendorf and Janice Mendonca, 2004, *Reusable Launch Vehicle Operations and Maintenance Guideline Inputs and Technical Evaluation Report: Subsystems, Volume 1*, 12 January, Research Triangle Park, NC, RTI International, prepared for the United States Federal Aviation Administration, pp. 87–90, at <64.29.75.106/Members/Government_Library/FAA_eDocuments_Collection/SubsystemVolume1-Final.pdf>.

[12] For example, see SPAR Aerospace Limited, 1985, *PAXSAT "A": Space Based Remote Sensing: Space-to-Space, Volume 1*, January, SPAR, Ste-Anne-de-Bellevue, Quebec.

[13] Designs for inspection satellites commonly include optical and infrared cameras, radar or lidar systems and signal detection functions, though they could also be outfitted with chemical or radiation detectors, or with X-ray systems to image the inside of the target satellite.

[14] Surrey Satellite Technologies, Ltd (SSTL) developed and launched the SNAP-1 satellite in 2000 for less than US$ 1.5 million. Such small payloads can catch rides on launches of larger satellites, drastically reducing launch costs. For example, SNAP-1 caught a ride on a Cosmos rocket along with the Chinese Tsinghua 1 and a larger US–Russian search and rescue satellite. See Lee Siegel, *Butane Fuel Propels Nanosatellites*, Space.com, 22 August 2000, at <www.space.com/news/bic_fuel_000822.html>; *SNAP-1 Summary*, Andrews Space & Technology database, at <www.spaceandtech.com/spacedata/logs/2000/2000-033b_snap-1_sumpub.shtml>, *A Practical, Proven*

Nanosatellite, Surrey Satellite Systems, Ltd., at <zenit.sstl.co.uk/index.php?loc=47>.

[15] *Falcon Overview*, Space Exploration Technologies Corporation, at <www.spacex.com/falcon_overview.php>; *Fact Sheet: Minotaur Space Launch Vehicle*, Orbital Sciences, 2003, at <www.orbital.com/NewsInfo/Publications/Minotaur_fact.pdf>; *Orbital Successfully Launches Minotaur Rocket Carrying U.S. Air Force's XSS-11 Satellite*, Orbital Sciences, press release 12 April 2005, at <www.orbital.com/Template.php?Section=News&NavMenuID=32&template=PressReleaseDisplay.php&PressReleaseID=498>.

[16] See Simon Collard-Wexler et al., op. cit., pp.103–104.

[17] Several in-depth studies of verification issues with lasers were completed in the early 1990s, including: Richard Garwin et al., 1991, *Laser ASAT Test Verification*, study group report, 20 February, Washington, DC, Federation of American Scientists; T. Broid et al., 1990, Laser Beam Verification, *Science & Global Security*, vol. 2, no. 1, p. 51; M. Fomenkova and O. Prilitsky, 1990, Atmospheric Scattering of Laser Radiation, *Science & Global Security*, vol. 2, no. 1, p. 79. See also Stanislav Rodionov, 1993, *Technical Problems in the Verification of a Ban on Space Weapons*, Research Paper No. 17, Geneva, UNIDIR; Regina Hagen and Jürgen Scheffran, Is a Space Weapons Ban Feasible? Thoughts on Technology and Verification of Arms Control in Space, 2003, *Disarmament Forum*, vol. 1, pp. 41–51.

[18] Geoff Fein, 2005, AFRL Moves Aerospace Relay Mirror System Demonstration to 2006, *Defense Daily*, 20 October, p. 5A; Aerospace Relay Mirror System (ARMS), GlobalSecurity.org, last updated 7 September 2005, at <www.globalsecurity.org/military/systems/aircraft/systems/arms.htm>.

[19] For example, see Tony Phillips, 1999, *Tuning in to April Meteor Showers*, NASA, April, at <science.nasa.gov/newhome/headlines/ast27apr99_1.htm>.

[20] A bolide is an asteroid, meteor or comet that explodes when it strikes the Earth's atmosphere.

[21] For example, see D.O. ReVelle, P.G. Brown and P. Spurny, Entry Dynamics and Acoustics/Infrasonic/Seismic Analysis for the Neuschwanstein Meteorite Fall, 2004, *Meteoritics and Planetary Science*, vol. 39, pp. 1605–1625; W.N. Edwards, P.G. Brown and D.O. ReVelle, 2005, *Bolide Energy Estimates from Infrasonic Measurements*, *Earth, Moon and Planets*, DOI: 10.1007/s11038-005-2244-4, at <aquarid.physics.uwo.ca/infrasound.htm>.

[22] *Decision on Possible Contribution of the CTBTO Preparatory Commission to a Tsunami Warning System*, 2005, CTBTO Preparatory Commission, Twenty-Fourth Session, Part I, Vienna, 4 March, at <www.ctbto.org/press_centre/press_release.dhtml?item=246>; Oliver Meier, 2005, CTBTO Releases Test Ban Monitoring Data for Tsunami Warning, *Arms Control Today*, April, at <www.armscontrol.org/act/2005_04/CTBTO.asp>.

[23] See Trevor Findlay, A Standing United Nations Verification Body: Necessary and Feasible, 2005, Canadian Centre for Treaty Compliance, *Compliance Chronicles*, no. 1, December, pp. 12–13.

[24] The Space Environment, *Space Security 2005: Briefing Notes*, Spacesecurity.org, at <www.spacesecurity.org/BN-TheSpaceEnvironment.pdf>.

[25] The 2001 cost for an infrasound station was US$ 350,000. *World Meteorological Organization*, at <www.wmo.ch/web/www/DPS/DPFS-ERA-US/ERA-COG-Doc8(2).F.doc>.

[26] Hydrophone stations are expensive to instal and costly to maintain, see *Monitoring Technologies: Hydroacoustics*, Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization, 2006, at <www.ctbto.org/verification/hydroacoustics.html>.

[27] As of October 2005, Defense Support Program Satellites are listed as having a unit cost of US$ 400 million, see Air Force Space Command: Air Force Link, at <www.af.mil/factsheets/factsheet.asp?fsID=96>.

[28] As explained by globalsescurity.org, “a modest satellite tracking radar or telescope typically costs several tens of millions of dollars, while the more elaborate radars can cost well in excess of US$ 100 million”, at <www.globalsecurity.org/space/systems/track-overview.htm>.

[29] The US Ground-based Electro-Optical Deep Space Surveillance (GEODSS) includes a total of five telescopes, constructed at a total cost of approximately US$ 250 million. The DARPA Space Surveillance Telescope development project has a projected budget of approximately US$ 15 million/year for six years. See United States Department of Defense, 2005, *Fiscal Year (FY) 2006/FY 2007 Budget Estimates, Research, Development, Test, and Evaluation, Defense-Wide, Volume 1: Defense Advanced Research Projects Agency (DARPA)*, February, p. 247, at <www.dod.mil/comptroller/defbudget/fy2006/budget_justification/pdfs/rdtande/DARPA.pdf>.

[30] The DARPA Deep View program is developing a high-resolution, high-powered radar for SSA and has a projected budget of approximately

US$ 11 million/year for six years; see United States Department of Defense, op.cit., p. 249.

[31] The US Space-Based Surveillance System (SBSS) is projected to involve a constellation of four satellites at US$ 189 million each, at <www.cdi.org/PDFs/FY05Appropriations.pdf> and <www.boeing.com/defense-space/space/space_systems/news/2004/q1/nr_040330n.html>. DARPA's Innovative Space-Based Radar Antenna Technology (ISAT) project developing an array of space-based radars has a projected budget of US$ 44 million/year for seven years, see United States Department of Defense, op. cit., pp. 248–249. On the other hand, Canada's Near Earth Space Surveillance (NESS) satellite, with fewer capabilities, has a planned cost of US$ 3–4 million, at <www.space.com/scienceastronomy/astronomy/ness_asteroid_000824.html>.

[32] Depends on overlap and cooperation with global air traffic control system.

[33] Replacement costs are considered infrastructure; operational costs are ground control and analysis.

[34] Costs depend on sensor choice, number of missions to be carried out and size of orbit changes required.

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