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Building up Transparency and Verification

MALTE GÖTTSCHE AND ALEXANDER GLASER (EDITORS)

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Editors
Malte Göttsche (RWTH Aachen University)
Alexander Glaser (Princeton University)

Assistant to the Editors
Jakob Brochhaus (RWTH Aachen University)

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Nuclear Monitoring and Verification Without Onsite Access

ALEXANDER GLASER AND IRMGARD NIEMEYER

ABSTRACT. *This chapter examines the possible contributions of remote and standoff monitoring for nuclear disarmament verification. In this context, satellite imagery could play a particularly important role. As spatial resolution of satellite imagery has increased to a level where further improvements are no longer critical, the technology is currently experiencing a second revolution thanks to high satellite-revisit rates, often multiple times per day, and thanks to broader access to satellite imagery by governments and the public. Other, complementary technologies that could reduce the importance of onsite inspections are wide-area environmental monitoring, which involves the regional collection of atmospheric or other samples, and perimeter monitoring, which seeks to confirm the declared operational status of a facility by treating it as a "black box" and drawing conclusions only by looking at items and materials as they enter or leave the facility. The chapter reviews the state-of-the-art of these technologies. It also assesses their potential for confirming the non-operational status or throughput of fissile-material production facilities and for monitoring nuclear weapons deployment, production, storage, dismantlement sites. While not the main focus of this chapter, we also examine the evolving role of remote monitoring techniques for the detection of undeclared facilities and activities. Relevant tasks include the ability to detect undeclared uranium mines, undeclared fissile material production, and undeclared weapons production or storage sites.*

Introduction

Onsite inspections play an important role in verifying compliance with nuclear nonproliferation and arms control agreements. Recent advances in remote and standoff monitoring may complement such inspections, which could make verification approaches more robust, less intrusive, and possibly also less expensive. Among the possible monitoring technologies and approaches, satellite imagery, wide-area environmental monitoring, standoff detection, and perimeter surveillance are often considered most promising for verifying nuclear disarmament without on-site access.

Satellite imagery has historically played a unique role in arms control verification. Today, satellite imagery also represents a key source of information for the implementation and verification of Nuclear Non-proliferation Treaty (NPT). Together with auxiliary data, it can be used as a reference source to aid in field and inspection planning, to detect changes and monitor activities at nuclear facilities, to verify the completeness and correctness of information supplied by a member state as well as to investigate alleged illegal activities related to nuclear nonproliferation, arms control or disarmament.[1] As spatial resolution of satellite imagery has increased to a level where further improvements are no longer critical, the technology is currently experiencing a second revolution thanks to high satellite-revisit rates, often multiple times per day, and thanks to broader access to satellite imagery by governments and the public.

Another technology that could complement onsite inspections is wide-area environmental monitoring, which involves the collection of atmospheric or other samples. This technique has the potential to detect undeclared activities or facilities on a regional and perhaps even global scale. Wide-area environmental monitoring could also be used in the vicinity of declared plants to confirm declared activities and reduce requirements for onsite access.

Yet another technology to consider is perimeter monitoring, which seeks to confirm the declared operational status of a facility by treating it as a “black box” and drawing conclusions only by looking at items and materials as they enter or leave the facility. Virtually any nuclear site has a security perimeter, typically set up and controlled by the host state or the operator of the plant. The main purpose of this perimeter is to deter, detect, and prevent unauthorized access to the plant and to prevent theft of nuclear materials or components, which is a concern for both insider and outsider threats.[2] It is only natural to consider building on this existing infrastructure to support independent monitoring of a site for verification purposes. This concept is particularly valuable for sites where inspector access is considered difficult, for example, due to security concerns raised by the host.

The chapter reviews the current state-of-the-art of these technologies and examines the ways in which they could support future disarmament verification regimes. In particular, the discussion highlights their potential for confirming the non-operational status or throughput of fissile-material production facilities and for monitoring nuclear weapons deployment, production, storage, dismantlement sites. While not the main focus of this chapter, we also examine the evolving role of remote monitoring techniques for the detection of undeclared facilities and activities. Relevant tasks include the ability to detect undeclared uranium mines, undeclared fissile material production, and undeclared weapons production or storage sites.

Technologies and Approaches

There are a number of technologies that could help reduce the requirements for onsite inspections in an arms control context. Before we consider specific verification objectives and approaches in the next section, here we summarize briefly the technical basics for those technologies that are most relevant or promising for this purpose.

Satellite imagery

While the era of military satellite reconnaissance began in 1960 with the U.S. Corona program, earth observation (EO) for civilian purposes started 1972 with the launch of Landsat-1 by the U.S. National Aeronautics and Space Administration (NASA). Landsat-1 recorded image data in three spectral bands (green, red, and near infrared) with a spatial resolution of 80 m. With the launch of IKONOS-2 in 1999, which provided a spatial resolution of one meter for the first time, the use of very high-resolution satellite imagery for monitoring nuclear sites and activities (for example, by the IAEA) gained greatly in importance.[3] Since then, EO solutions have continued to expand and diversify, in terms of spatial, spectral, and temporal resolution of image data, and in national ownership. More and more countries have planned to launch EO satellites in order to respond to national policy or security interests, to assist in developing a national space infrastructure, and to expand current commercial data offerings.

Sensor	**Company (Country)**	**Launch date**	**No. of satellites**	**Spatial resolution (in m)**	**Swadth (in km)**
Optical sensors					
WorldView Legion	*Maxar Techn. (USA)*	*2021*	*5 ?*	*0.29 (PAN)* *1.16 (VNIR)*	*tba*
WorldView 3	Maxar Techn. (USA)	08/2014	1	0.31 (PAN) 1.24 (VNIR) 3.7 (SWIR)	13.1
EROS-C	ImageSat Int. (Israel)	2020	1	0.38 (PAN) 0.76 (VNIR)	11.5
Geo-Eye 1	Maxar Techn. (USA)	09/2008	1	0.41 (PAN) 1.65 (VNIR)	15.3
WorldView 2	Maxar Techn. (USA)	10/2009	1	0.46 (PAN) 1.85 (VNIR)	1.4
WorldView 1	Maxar Techn. (USA)	09/2017	1	0.50 (PAN)	17.1
SuperView-1/ GaoJing-1	Beijing Space View Techn. (China)	12/2016 01/2018	4	0.50 (PAN) 2.0 (VNIR)	12.0
Synthetic aperture radar (SAR) sensors					
TerraSAR-X Tandem-X	Airbus Defense and Space (Germany)	06/2007 10/2010	2	Down to 0.25*	4 x 3.7 or 2.5 x 7.5*
ICEYE	ICEYE (Finland)	01/2018-07/2019	5 (up to 18)	Down to 0.25*	5*
Capella-2/ Sequioa	Capella Space (USA)	08/2020	1 (up to 36)	Down to 0.3*	5 x 20 or 10 x 10*

Very high spatial resolution imaging sensors, ordered by spatial resolution (<0.5m). PAN: panchromatic; VNIR: visible and near infrared spectrum; SWIR: shortwave infrared spectrum. Sources: www.satimagingcorp.com/satellite-sensors; Operators' websites; Earth Observation Portal at *directory.eoportal.org*; Observing Systems Capability Analysis and Review Tool (OSCAR) at *www.wmo-sat.info/oscar*. *) depending on acquisition mode (here: highest spatial resolution possible)

The advent of small satellites has led to another revolution in earth observation. Small satellites typically have a mass of less than 500 kg and are smaller than a kitchen stove, but they can still deliver sub-meter resolution imagery and high-definition videos. Due to much lower costs associated with development and launch, large constellations of small satellites have become possible, which enables for more frequent revisits, monitoring, and change detection of areas of interest. While existing satellite constellations can already take daily snapshots of the entire planet, a time resolution on the order of hours could soon be possible. The table above lists the very high-resolution earth observation sensors in space today, providing imagery at a resolution of better than one meter.

Optical sensors operate in the optical region of the electromagnetic spectrum traditionally defined as radiation with wavelengths between 0.4 and 15 μm. The specific wavelengths within the electromagnetic spectrum that are observable to satellite borne sensors are well understood and therefore the majority of earth observation satellites collect wavelengths in regions that have the highest potential for information to be collected by the sensor. These areas include visible wavelengths, near-infrared, thermal and radio wavelengths. The visible and near infrared (VNIR) wavelengths are very common for image analysis since they are the easiest for humans to visually interpret as they closely match with the wavelengths the human eye can detect. Commercially available sensors with high spatial resolution record information in these bands. Some of these sensors, such as the Worldview-3 sensor, also collect information in the shortwave infrared whereas others, like Kompsat-3A, collect in the mid infrared.

While these multispectral sensors acquire data in a number of bands covering only parts of the electromagnetic spectrum, hyperspectral sensors record the reflected radiation in several hundreds of very narrow contiguous or overlapping wavelength bands, providing a continuous spectrum from the visible to shortwave infrared. As specific surfaces leave unique fingerprints in the electromagnetic spectrum (also known as spectral signatures), hyperspectral data allows for identification of surface materials. New spaceborne hyperspectral sensors have been launched recently (DESIS, PRISMA, and Jilin-1) and others will be launched in coming years. However, the low temporal resolution (revisit time) and the medium spatial resolution of 20–30 m for some of these sensors may be a limiting factor for the application of spaceborne hyperspectral data for arms control and disarmament verification.

Synthetic Aperture Radar (SAR) is a valuable active sensor type since it penetrates most cloud cover and offers a different set of information for interpretation compared to optical sensors. SAR data requires a different set of processing techniques and demands a different approach for processing and analysis compared to the other earth-observation sensors mentioned above. The frequency bands generally used for these activities are the X, C, and L bands. Some of the commonly used SAR sensors include TerraSAR-X, TanDEM-X, COSMOS-Skymed, Capella, Radarsat, and Sentinel-1 SAR.

As satellite imagery providers deploy new constellations of satellites, with the aim of images covering all landmasses in the world several times a day, the quality and quantity of this data is increasing rapidly as are the methods to process and analyze the datasets. The resulting repositories of satellite imagery will offer analysts distinct insights into nuclear facilities and nuclear activities from space worldwide. The deluge of data, together with the variety of related metadata, however, requires the further automation of pre-processing, in order to produce geometrically and spectrally corrected input imagery, including data file conversion to a model standard, orthorectification and co-registrations, radiometric normalization and screening for artefacts caused by clouds, cloud-shadow, snow, and other confounding factors.[4] Advancements of methods are also necessary for extracting the relevant information from satellite imagery, such as infrastructure changes, as visual interpretations of single satellite image scenes can no longer be expected to address the analysis requirements for such large satellite imagery repositories. New robust data science methods can offer analysts automated alerts that flag for instance changes occurring within a nuclear facility's infrastructure.[5] If changes were detected, automated prompts and traditional manual evaluations by analysts of change would then be initiated. A number of studies have demonstrated the potential of data science methods for nuclear verification, such as statistical time series analysis, deep learning methods, and convolutional neural networks.[6]

Wide-area environmental monitoring

The IAEA has been using *location-specific* environmental swipe sampling techniques for safeguards purposes since the 1990s. This sampling technique is used on a routine basis during inspections of a variety of nuclear-fuel cycle facilities today, and it has proven very effective and inexpensive and is considered a mature technology. While swipe sampling could also play a relevant role in nuclear disarmament verification, for example, by providing confidence in the absence of certain materials at specific facilities, it requires access to the inspected facility and is therefore not part of the discussion here.[7] Beyond location-specific environmental sampling, the 1997 Additional Protocol also considered the use of wide-area environmental sampling (WAES), which it defined as follows:

> “Wide-area environmental sampling means the collection of environmental samples (e.g., air, water, vegetation, soil, smears) at a set of locations specified by the Agency for the purpose of assisting the Agency to draw conclusions about the absence of undeclared nuclear material or nuclear activities over a wide area”
> (INFCIRC/540, Article 18).

Wide-area environmental sampling is not currently used for IAEA safeguards purposes, and it would have to be first approved by the IAEA Board of Governors before it could be.[8] Already in February 1995, however, the IAEA Secretariat concluded that environmental monitoring is “an extremely powerful tool for gaining assurance of the absence of undeclared activities at and near such nuclear sites.”[9] In order to further clarify the potential of WAES, an extensive study set out to determine the feasibility, practicability, and costs of environmental monitoring techniques to detect undeclared nuclear activities on a country-wide or large-area basis, particularly in areas that do not contain declared nuclear or nuclear-related sites.[10] STR-321 found that atmospheric sampling appeared to be the technique with the greatest detection probability per sample of those sampling methods that were considered. However, the costs of operating a sensor network could be very high and would strongly depend on the type of facility or activity, the target region covered, and the acceptable probability of detection and false-alarm rate. Overall, undeclared plutonium separation (reprocessing of spent fuel) would be more easily detectable than most other relevant activities. Gas-centrifuge uranium enrichment plants would be most difficult to detect, which has been confirmed by some other studies later on.[11] STR-321 also highlighted the uncertainties in the analysis and pointed out that additional work would be useful in validating some of the key assumptions used as input to the study on which the results heavily depended. Research on WAES continues, and several promising new techniques and approaches have emerged since STR-321 was first published.

The original IAEA definition of WAES is relatively narrow as it only considers the collection of *physical* samples. The IAEA also assumed that some form of local or regional access would be required and that, for the same reason, the host party would be collaborating with the effort and even accompany the inspectors at all times. Below, we consider a broader view of WAES and, specifically, use the word "monitoring" instead of "sampling" (WAEM vs WAES). In particular, a collection of physical samples may not always be necessary for WAEM; for example, laser-based techniques (such as LIDAR) could probe the air above a suspected location to detect trace amounts of gases or particulates, and antineutrino detectors could detect undeclared reactors from a distance. Similarly, the seismic, acoustic and radionuclide stations of the International Monitoring System (IMS) operated by the CTBTO could be considered part of a WAEM network. Data from different sensor platforms could be combined to enable a more robust monitoring network that relies on more than one signature. Finally, the use of airborne sensors may not always require the active collaboration of the inspected party if the use of such a platform has been generally agreed upon and formalized as part of a [regional, bilateral or multilateral] arms control agreement. There have been several important technical developments since the first extensive studies of WAEM in the 1990s that have the potential to make the approach more viable today; they include:

Availability of mobile sensor/detector platforms. The last decade has seen disruptive advances in drone or unmanned-aerial-vehicle (UAV) technology used for a variety of civilian and military purposes.[12] Deploying sensors for WAEM on drones or swarms of drones could have fundamental advantages compared to fixed sensor networks. First, they could be deployed regionally, for example, as part of a regional arms control agreement. Second, given the dynamic nature of the network, mobile platforms could provide higher levels of assurance as their "behavior" is more difficult to predict and non-compliance therefore more difficult to conceal.

Advances in data science and machine learning. Large datasets of noisy sensor data could be processed by advanced machine-learning techniques that have only become available over the past few years.[13] This automated process may flag suspect patterns in the data so that a safeguards or verification specialist can further examine the region or location. There are numerous efforts underway that seek to quantify the potential of data analytics using data-fusion from multiple sensor platforms. Such efforts are often based on the premise that single-modality analysis cannot “deliver a global-scale, real-time capability to detect, locate, and characterize low-profile proliferation.”[14]

State-of-the-art modeling capabilities. Atmospheric signatures are generally considered most promising for several types of nuclear fuel-cycle facilities. Here, the atmospheric-transport modeling (ATM) capabilities have increased dramatically over the past two decades. This is often driven by research and development in the area of climate science and supported by much improved weather data availability. ATM can be used for backward and forward modeling. In the case of backward modeling, ATM can be used to identify possible source locations and time of release once an unusual activity is detected; in the case of forward modeling, given a suspect location or event, ATM can be used to determine the best sampling locations for an upcoming campaign in real time. Still, in many circumstances, the usefulness of such modeling efforts would rely on available baseline data, which would include in particular emissions from declared facilities. In order to maximize the usefulness of ATM and of WAEM in general, declarations of emissions from nuclear facilities worldwide would be very beneficial. For example, operators of commercial reprocessing plants could provide daily or hourly data on krypton-85 emissions. So far, operators have been reluctant to do so.

Standoff-detection is considered here as a special, targeted variation of wide-area environmental monitoring. In this case, the facility is known and declared, but access to the site itself is difficult or impractical for security or safety reasons. The same signatures and sensor types that can be considered for WAEM are also relevant for standoff-detection, but the host would actively support or accept the deployment of sensors near the site. The main use case for standoff detection could be at some known military, sensitive facilities to avoid or minimize access for inspectors. Many of the challenges associated with large-scale (regional) WAEM, which seeks to provide confidence in the absence of undeclared facilities, are much less pronounced in the case of standoff detection given the proximity of the sensors to the site that is being monitored. For example, it is relatively easy to confirm the operational status of nearby reactors using antineutrino detectors; it is vastly more difficult to detect them at larger distances for “regional reactor discovery” as further discussed below.

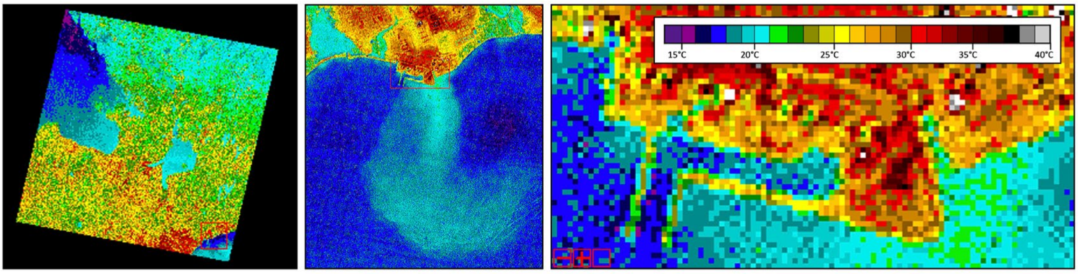
Perimeter portal control continuous monitoring

Perimeter monitoring could play a future role to support nuclear disarmament verification by reducing the need for onsite inspections at sensitive sites associated with a nuclear weapons program. Indeed, verification of the Intermediate Nuclear Forces (INF) Treaty relied extensively on perimeter monitoring at two ballistic missile production sites in the United States and the Soviet Union. The technology has some important drawbacks, however, which has so far limited its general adoption for verification purposes. In particular, the IAEA has been reluctant to adopt perimeter control as part of its safeguards system; there are various reasons for that. First, the IAEA deals mostly with nuclear materials, often in bulk form, whereas INF required monitoring of large and bulky missile stages and rocket motors. Perimeter control with portal monitors becomes more challenging as the items of inspection become smaller and more difficult to detect. Second, by monitoring the perimeter only, one cannot preclude that prohibited activities are conducted within the facility, which may enable some “fait-accompli” breakout scenarios and make timely detection of non-compliance difficult or impossible. Third, perimeter control tends to be costly, in particular, because it typically requires resident inspectors. For example, INF inspections were extremely expensive compared to IAEA safeguards costing about 50% of the IAEA budget at the time, which covered at the time more than 900 facilities in almost 60 countries.[15] Finally, and perhaps most importantly, the IAEA generally avoids physical security-like measures as part of its inspection activities; in particular, it’s not part of the IAEA culture to conduct personal or vehicle searches, beyond its authority. Scheinman and Kratzer (1992) acknowledged that “the rejection of perimeter monitoring under NPT-IAEA is at least partly attributable to institutional and attitudinal factors that have tended to overemphasize the need for complete materials balance accountancy and place unnecessary restrictions on the use of surveillance and containment measures.” Overall, with few exceptions, there is relatively little experience with perimeter portal continuous monitoring for verification purposes, and the most important effort ended when the inspection regime of the INF treaty ended in 2001.

Given its low salience as a verification technology, technologies relevant for perimeter control have developed slower than in other areas. Today, there exist advanced and more sensitive instruments, which enable measurements that were previously impractical. Machine learning techniques have further enabled characterization of radiation signatures even when the signal-to-noise ratio is extremely low. The “Miniature Integrated Nuclear Detection System” (MINDS) is able to identify radioactive sources within seconds, for example, in automobiles that stop or slow down at a toll booth.[16] The system uses a supervised machine-learning algorithm and can be trained with large data sets to make it robust against false-positives. The system also senses intentionally concealed or mask radiation signatures, for example, when attempts are made to pass shielded containers through a portal monitor. Systems like these have yet to be tested on a broader scale for verification applications.

Monitoring Regimes and Verification Objectives and Approaches

We consider a number of verification objectives for possible future arms control treaties. Such agreements could include limits on the number of nuclear weapons, including those in storage, or a ban on certain weapon types. We also consider objectives that could be relevant for agreements that constrain the production or use of fissile material for military purposes such as a fissile material (cutoff) treaty or the monitored international storage, disposition, or elimination of excess materials. In many cases, sensitive military nuclear sites would have to be monitored, and minimizing the need for onsite inspections may often be considered advantageous.



Surface temperatures at a nuclear power plant, analyzed based on LANDSAT-7 image acquired over the site in August 2002. Using the temperature information from the thermal band (60 m spatial resolution), the surface temperatures can be displayed on a given scale. For better illustration of the temperature distribution on the surface, they were fused with the 15-m panchromatic band.

Confirming non-operational status of fissile-material production facilities

The operation of nuclear facilities is associated with some specific activities or features on the earth surface, such as vehicles in parking spaces, delivery traffic and equipment. While these types of surface objects and their movements can easily be monitored using very high-resolution satellite imagery, the existence of thermal emissions could give the essential indication that a facility is in operation. The absence of these activities and features on the surface can be used to confirm the non-operational status of nuclear facilities, and, depending on the type of facility, thermal infrared imagery can play an important role in this context. However, spaceborne thermal infrared sensors with a commercial payload are limited to the Landsat-8 and ASTER sensors with a spatial resolution of 120 m and 90 m, respectively. Since no developments as to spatial resolution are expected for commercial sensors soon, they will remain the only source of thermal infrared information from space for the medium-term future.

Despite the poor resolution, thermal infrared remote sensing data can provide verification-relevant information in case of significant thermal signatures of the facility. After converting the thermal infrared data to emissivity and temperatures, image fusion with bands of higher spatial resolution facilitates the interpretation of the temperatures. Using anomaly detection tool are useful for extracting “hot spots” in a specific region or the whole scene (see figure).

Confirming production-as-declared status of fissile-material production facilities

In general, it is easier to verify the absence of something than it is to verify an upper or declared limit. This is also true for nuclear fuel-cycle facilities, where it is much easier to verify the shutdown status than the throughput of a plant. Onsite access to sites and facilities is always desirable for confirming the “operation-as-declared” status of plants but remote or standoff monitoring may be preferable in some circumstances due to security or other concerns. Here, we are particularly interested in nuclear reactors, reprocessing plants, and uranium enrichment plants.

Nuclear reactors. From a verification perspective, the main concerns associated with the operation of nuclear reactors are activities that could be related to undeclared plutonium production; these include high-than-declared power levels of the reactor, undeclared irradiation of target materials in the core, and diversion of irradiated or spent fuel from the reactor core or the spent fuel pool. The relative importance of these distinct concerns varies between research reactors (10–100 MW thermal) and power reactors (1000–3000 MW thermal), but traditional safeguards have proven very effective in addressing them. In the case of nuclear weapon states, possible exceptions may include some high-powered research reactors that are partly or primarily used for military applications, including for example tritium production or irradiation testing of naval fuel. In these circumstances, there could be a complementary role for perimeter or standoff monitoring of these sites. In particular, there has been some interest in detecting antineutrinos, which are emitted in the fission process and can confirm the operational status and power levels of nuclear reactors. To a more limited extent, this method can also be to track fuel changes over time.[17] Given the complexity and costs of the technology, the use of antineutrino detectors for reactor monitoring is often considered impractical, especially if the same verification objectives can be achieved with other, more traditional means.

Uranium enrichment plants. The IAEA has significant experience with safeguarding centrifuge enrichment plants.[18] In recent years, safeguards approaches have been strengthened further, and they now also include instruments that enable real-time monitoring of the enrichment level of the product using the “Online Enrichment Monitor” (OLEM), an instrument currently used in Iran.[19] Similarly, it may be possible to also monitor in real-time the throughput of a gas-centrifuge enrichment plant, which together with enrichment monitoring provides a complete picture of ongoing operations and allows timely detection of a “breakout.”[20] The very same safeguards technologies and approaches could be used in nuclear weapon states; in fact, centrifuge enrichment plants in France, the United Kingdom, and the United States are already under IAEA safeguards. There is far less experience with safeguards on plants using Russian and Chinese centrifuge technology, and there is no experience in India, Pakistan, North Korea, and possibly Israel.

There is one potential use case for perimeter monitoring at very large enrichment plants that are unsafeguarded today and where implementation of traditional safeguards techniques could be considered too complicated or insufficient, especially when retrofitted into an already existing plant. In fact, in the 1970s, perimeter monitoring was considered as a safeguards approach for plants under construction or planned at the time.[21] Fundamentally, the concept is based on tracking and measuring the material entering and leaving the plant. The number of UF_6 cylinders involved is relatively small even for a plant with a capacity in the million SWU/yr range (see figure). Based on these measurements, the separative work of the plant could be independently estimated, though not necessarily in a timely manner. In the context of a fissile material cutoff treaty or a declared moratorium on fissile material production, this approach could also be used to infer the non-production of HEU. While it could be difficult to detect extraction of the highly enriched material from the site (due to its small volume, as illustrated in the figure below), there would be a significant and easily detectable shortfall in the expected low-enriched product leaving the plant.

Reprocessing plants. Safeguarding reprocessing plants is very difficult and expensive even in non-nuclear weapon states where the IAEA may be involved in the planning and construction stages of the project; in fact, once operational, Japan’s Rokkasho plant would absorb about 50% of the current IAEA inspection effort. Concepts for safeguards at reprocessing plants in weapon states under a Fissile Material Cutoff Treaty would be very similar to those developed for Rokkasho.[22] Retrofitting safeguards into existing plants would be extremely difficult and, in some cases, impossible. As an interim measure, perimeter monitoring could play a limited role, and monitoring of krypton emissions directly at the stacks could be used to estimate declared plutonium production at the plant. Altogether, from a verification perspective, it would be much preferable to shut down these few existing plants that are unsafeguarded today.

Uranium entering and leaving a large enrichment plant over a two-week period. Shown on the left are the feed cylinders needed to supply natural uranium for a one-million SWU/yr plant and the product cylinders that can be produced with this material. Shown on the right is a misuse scenario, where one significant quantity of HEU is produced. While it may be difficult to detect the removal of small HEU cylinders from the plant, a significant amount of LEU product is unaccounted for. A verification approach based on perimeter portal continuous monitoring may be able to confirm as-declared operation of such a plant without onsite access.

Monitoring nuclear weapons deployment, production, storage, dismantlement sites

Nuclear weapons deployment, production, storage, and dismantlement sites can be considered the most difficult sites to capture with onsite inspections. At all these sites, there are extraordinary safety and security concerns, which also apply to workers and personnel but are exacerbated for international inspectors. Among these facilities, there is some experience with access for inspectors to deployment sites, especially under INF and START,[23] but even here remote monitoring has played a critical role.

The 1972 SALT agreements first introduced the concept of using satellites (falling under “national technical means”) for verification purposes, and the parties undertook “not to interfere with the national technical means of verification of the other party” and “not to use deliberate concealment measures” (SALT, Article V). START expanded on this concept by introducing cooperative measures; in particular, at the request of the other party, road-mobile launchers of ICBMs could be openly displayed by opening the roofs of their garages with the launchers located “next to or moved halfway out of such fixed structures”

(START, Article XII). Future arms control agreements could similarly rely on satellite imagery to confirm numerical limits on launchers; it is unlikely, however, that satellites could play a primary role in confirming warhead limits at deployment or other types of facilities in this category. Warheads are small and can be moved more quickly in inconspicuous vehicles. In any event, quasi continuous monitoring of a site using satellites has to be considered difficult and perhaps impractical even with large satellite constellations. Very few countries have the capabilities to re-task satellites on short notice, and quasi-continuous monitoring is further constrained by cloud coverage and nocturnal periods, during which optical satellites cannot be used for most monitoring missions.

In anticipation of short-notice (challenge) inspections, satellite reconnaissance may be considered appropriate to monitor the standdown status of a site during a limited amount of time, for example, to confirm that no large trucks enter or leave the site during a well-defined, limited time window before inspectors arrive at the site.

Given the presence of highly sensitive items and operations at weapons assembly, maintenance, and dismantlement sites, onsite inspections at these sites would have to rely on managed-access concepts.[24] While possible and successfully used on a small scale in the past, managed-access inspections are complex and would be particularly challenging at sites where warheads are produced or maintained. It is possible that, in some cases, perimeter control without onsite access would be a preferable and more viable approach for such sites; only when the active use of a site ceases, a close-out inspection would be used to confirm the absence of all treaty accountable items or activities.

The 1987 Intermediate Nuclear Forces (INF) Treaty between the United States and the Soviet Union pioneered the concept of perimeter control for arms control purposes.[25] As part of the treaty, both parties had the right to monitor the portals and to patrol the perimeter of one missile production site in each country for up to thirteen years, i.e., from 1988 through 2001. Up to 30 resident inspectors were allowed at the portals of the selected facilities, and inspection activities Inspections included measurements (weight and dimensions), infrared profiling to monitoring traffic, x-ray imaging, and a limited number of visual inspections.[26] As planned, these inspections ended in May 2001.

Perimeters could either consist of attended stations or possibly be made “more minimal” through measures such as unattended radiation detection portals at strategic locations. Perimeter systems could be particularly attractive if only a handful of sites with smaller footprints require monitoring.[27] Using other sensors aimed at the detection of emissions from the plants are less meaningful as in the case of sites used for production or processing of nuclear materials. In general, no emissions can be expected from nuclear weapons deployment, production, storage, dismantlement sites.

Another possible approach to conduct inspections at sensitive nuclear facilities could be to have only the host access the site while the inspector follows the activities remotely, i.e., either from directly outside the facility or even from a distant location (possibly without traveling abroad at all). Communication between the host and the inspector could be established using various methods and technologies. A straightforward method would be a live video stream, but other technologies could also be considered.

The main advantage of such “secure virtual inspections” – a term first proposed by the Committee on International Security and Arms Control (CISAC) of the National Academy of Sciences – could be to avoid any access of inspectors to facilities that are considered particularly sensitive. Virtual inspections could be considered a variation of managed-access inspections, which have been demonstrated but are a necessarily complex undertaking. Managed access generally requires extensive preparations by the host party; in particular, the facility selected for inspection may have features or include items and activities that are irrelevant for the inspection task itself but may be considered sensitive for other reasons. In contrast, imagery transmitted during a virtual inspection would only include what is directly relevant for the task while essentially excluding everything else. In the case of a live video stream, key objective for the inspector would be to have confidence in the fact that the stream is live and that the transmitted data (i.e., the video feed) has not been tampered with. It may also be necessary to confirm that the video is being transmitted from the correct location. One way to address some of these challenges could be to include unique items or patterns in the (video) data.[28] These objects or patterns would only be known to the inspector and they could change in short time intervals, which could provide additional confidence in the integrity and “freshness” of the data and make replay attacks difficult or impossible.

This concept could have similar benefits for standard IAEA safeguards inspections. In particular, if such an approach was demonstrated and approved, certain routine procedures (for example, applying or verifying the integrity of seals) could be conducted using such an approach with inspectors monitoring relevant activities from Vienna.

A variation of such virtual inspections, where host and inspectors are at different locations, has been proposed as part of a possible denuclearization of North Korea,[29] but it could equally well be applied to other bilateral or multilateral arms control settings. Here, treaty accountable items would be jointly containerized and sealed – for example, using electronic seals – before the host takes them to secret locations for storage. The seal would be designed such that it displays unique, frequently changing alphanumeric codes (similar to an RSA SecurID device). From then on, inspectors could remotely request readout and transmission of these codes. For a properly designed system, the host party would only be able to provide the correct answers if the seal remains operational, confirming the state-of-health of the seal and the content of the respective container. Approaches like these could simplify verification of limits on containerized treaty-accountable items substantially.

Detecting Undeclared Facilities or Activities

This analysis focuses on verification objectives that can be achieved without onsite access to relevant declared sites. As such, detecting undeclared facilities is not a primary focus of our discussion. Still, some of the technologies and approaches discussed here have also or even mainly been used to detect previously unknown nuclear facilities.[30] Some prominent examples include facilities in Iran, Syria, and North Korea. We therefore briefly explore existing emerging capabilities of satellite imagery and wide-area environmental monitoring for detecting undeclared facilities.

Detecting undeclared uranium mines

The ability to remotely detect with high confidence undeclared uranium mines would be a useful capability not only to support nuclear disarmament verification but also to strengthen the existing nonproliferation regime. Declaring mining activities is already a part of the Additional Protocol, which requires states to provide the IAEA with "information specifying the location, operational status and the estimated annual production capacity of uranium mines" (INFICRC/540, Article 2). Satellite imagery can support related IAEA assessments and safeguards by providing independent information on the status of uranium mines, which are often located in remote and difficult-to-access areas. There have also been efforts to characterize known uranium mines, in particular open-pit mines, using hyperspectral satellite imagery, which can provide information on the elemental composition of the features in the scene,[31] i.e., such imagery can be used to identify ore pits, waste rock, tailings ponds, etc. Similar imaging techniques could be used to detect undeclared mines though other mining techniques, such as underground mines,[32] are more difficult to detect, especially when an adversary makes an effort to conceal them. In-situ recovery or in-situ leaching (ISL) dominates commercial uranium recovery today, and it may be particularly difficult to detect. ISL has very few surface signatures as no rock is ever brought to the surface and no tailings piles exist. Only injection and extraction wells are required. Undeclared ISL mining operations on a limited scale, large enough to support a small nuclear weapons program could be particularly difficult to detect. Undeclared uranium could also be produced as a byproduct of other mines, further complicating the detection effort.[33]

North Korea provides one important example as there have been some recent efforts to understand mining activities in the country, partly based on hyperspectral satellite imagery.[34] As part of this case study, imagery of the tailing piles from the only known uranium mine in North Korea, the Pyongsan uranium mining and milling complex, were used as a reference point for multispectral analysis. An algorithm then used the signature of the imagery from these known tailing-piles to look for similar signatures elsewhere in the country. In another part of the analysis, geological maps of North Korea were compared with similar maps of South Korea, where uranium-ore deposits are well documented. Findings from these complementary approaches can be combined to identify possible candidate sites for additional mines in the country. These locations could then be monitored more closely. While such an effort would be more difficult to implement in a larger country or geographical region, the use of state-of-the-art machine-learning algorithms combined with frequent-revisit satellite imagery shows significant potential in detecting undeclared mining activities.

Detecting undeclared fissile material production

Clandestine production of fissile materials could focus on production of plutonium, highly enriched uranium, or both. At a minimum an undeclared reprocessing or enrichment plant would be needed as we assume that declared facilities would be under safeguards. In the case of plutonium production and in addition to the secret reprocessing plant, a dedicated reactor would be required also, though abrupt diversion of existing spent fuel, even when under safeguards, to the secret reprocessing plant is of concern also.[35]

Nuclear reactors. The minimum power level of a nuclear reactor needed to support a small nuclear weapons program is on the order of 30 MW. Such a reactor, fueled with natural uranium, can produce about 8 kg of plutonium per year. The footprint of such a plant is sufficiently large to be easily recognizable in satellite imagery. The visual signatures of reactor sites are typically rather unique. Indeed, several historic cases exist where such a plant was discovered while under construction, even when efforts were made to conceal the nature of the construction project (see figure). Though there may be more elaborate deception efforts, such as underground construction, satellite imagery provides a powerful monitoring tool to detect undeclared reactors.

In addition to satellite imagery, antineutrino detection has been considered for “regional reactor discovery, exclusion, and monitoring” of nuclear reactors.[36] The fundamental constraint is size and cost of a system that would have the capability to detect an unknown reactor in the 30-MW range from a meaningful distance, i.e., from hundreds of kilometers away. Such long-range detection does not appear feasible “for the foreseeable future due to considerable physical and/or practical constraints.”[37] There may be a possible role for the technology when deployed in a small region as part of a denuclearization agreement, when access to sites formerly part of a weapons program is severely constrained.

Uranium enrichment plants. Uranium enrichment plants, especially those based on gas-centrifuge technology, are notoriously difficult to detect. The footprint of these plant is rather small, and the visual signatures tend to be non-specific. Centrifuge enrichment plants require little electricity and no cooling infrastructure, which also facilitates underground construction. Similarly, emissions from centrifuge enrichment plants, in particular, atmospheric emissions of uranium gas or particles (UF_6, UO_2F_2) tend to be very small and quickly become non-detectable.[38] Here, it may be more promising to seek detection of an undeclared conversion plant, which produces the UF_6 feedstock needed for the enrichment process. Emission rates from conversion plants have been estimated to be 100–1000 larger than those from centrifuge enrichment plants.[39] Wide-area environmental monitoring could in principle have the potential to detect these signatures, especially when part of a regional (not global) monitoring effort. As in the case of reprocessing plants (discussed next), simple countermeasures exist to make WAEM much more challenging; for example, high-efficiency particulate air (HEPA) filters could reduce plant emissions by several orders of magnitude; similarly, an undeclared conversion or enrichment plant could be located close to a larger declared plant. Overall, the ability to detect undeclared enrichment plants remains a major challenge for verification of nuclear arms control and disarmament. Given that most weapon states have fissile-material stockpiles that far exceed their requirements, even based on their current warhead stockpiles, new production of fissile materials may not be considered a major concern for the foreseeable future.

The Al Kibar site (35.708 N, 39.833 E) in Syria in August 2007, shortly before it was destroyed by Israeli aircraft. The construction of an undeclared plutonium production reactor had apparently been underway,[40] possibly with foreign assistance. *Credit: Google Earth.*

Reprocessing plants. Unlike in the case of uranium enrichment plants, plutonium separation from spent fuel at reprocessing plants creates a unique atmospheric signature. Dissolution of irradiated nuclear fuel inevitably leads to the release of radioactive fission products including some noble gases, which are typically emitted from the plant; among these, krypton-85 is a clear indicator of spent fuel reprocessing. The isotope has a half-life of 10.8 years and has been accumulating in the atmosphere since reprocessing started on a large scale in the 1950s. The fundamental challenge is to detect weak krypton-85 signatures from a small plant against the global background and, more importantly, the continual fluctuations in krypton levels due to emissions from large declared plants and current weather conditions. It is widely believed that a global krypton-85 monitoring network having enough stations to enable detection of emissions from a small, unknown reprocessing plant anywhere on the globe would be prohibitively expensive.[41] Moreover, with known weather conditions, emissions from a large plant could be used to obfuscate the signal from a smaller undeclared plant.

Detecting the reprocessing plant itself, perhaps even during construction, using satellite imagery has to be considered difficult. The footprint of such a plant could be very small and the visual signatures could be similar or identical to other industrial plants. The possibility of clandestine construction of such a "simple, quick processing plant" has been a concern since the 1970s.[42] Especially when combined with the scenario of abrupt diversion of spent fuel from a declared site, timely detection of such a plant using krypton emissions remains a verification challenge that is fundamentally difficult to address.

Detecting undeclared weapons production or storage sites

Detecting undeclared weapons production or storage sites is probably among the hardest verification challenges for nuclear disarmament. There are no good assumptions about where to look for possible sites and what signatures to look for. Facilities could be underground and would be nondescript except perhaps for a security perimeter. In any event, a non-compliant party is likely to make every effort to make remote detection of such a site difficult, especially in a "timely" manner.

Satellite imagery may be the most viable monitoring technology available to international organizations for the task of detecting such sites. Governments may be able to access or acquire additional intelligence, in particular signal and human intelligence (SIGINT and HUMINT), which we do not consider here. Such original intelligence would enable closer monitoring of a candidate site with reconnaissance satellites. Once a site has been flagged for further examination, an archive of historic satellite imagery of the same location could be used to reconstruct the history of the site after the fact.

When no prior information about possibly suspect locations is available, the task becomes much more difficult. Given the sheer quantity of satellite imagery produced today, human analysts can no longer process this imagery in its entirety, and machine-learning techniques will become increasingly important in analyzing the data and flagging scenes for further examination and human review. There are already some case studies where machine-learning techniques have been successfully used to identify sites with national-security relevance.[43] In general, machine-learning algorithms require large amounts of training data in order to perform well. This is a particular challenge for the task at hand. Few warhead storage sites exist worldwide and there are no obvious unique visual features that could play a role in the training phase of the algorithm to answer the question of what makes a warhead storage site.

Conclusion and Outlook

> *“On-site inspection has been vastly overrated in the history of arms control.”*
>
> Allan Krass, 1985

Onsite inspections are usually considered as a final, decisive measure in nuclear verification, both for NPT safeguards, for a possible verification of the CTBT, and for existing arms control agreements including New START. Onsite inspections of declared nuclear facilities are particularly well established in IAEA safeguards, with tailored approaches for different types of facilities. With a view to future disarmament agreements, it is safe to assume that onsite inspections will continue to play an important role. Notably, onsite inspections are not particularly controversial when inspected plants are operated for peaceful purposes, for example, as part of a fissile material (cutoff) treaty.

In the broader context of nuclear disarmament verification, onsite inspections can also be effective for nuclear weapons deployment, production, storage, and dismantlement sites. Past and ongoing nuclear disarmament verification initiatives such as the International Partnership for Nuclear Disarmament Verification (IPNDV)[44] and the Quad Nuclear Verification Partnership (QUAD)[45] have focused on how to develop and implement approaches and techniques for these scenarios. There might be, however, some room for complementing or minimizing the role of onsite inspections by applying appropriate remote and standoff monitoring technologies and approaches, as presented in this chapter.

Satellite imagery has historically played an important role in arms control verification, and its potential is likely to grow further in coming years. This will be partly due to dramatically increased coverage, now often allowing multiple revisits of the same site per day. At the same time, the growing interest in satellite-based synthetic aperture radar (SAR) sensors will make earth observation more robust against unfavorable conditions, including cloud coverage or even some deception efforts. One important mission of satellite imagery has traditionally been military reconnaissance and the search for undeclared (nuclear) facilities, where satellites can play a role in detecting undeclared uranium mines, fissile material production, and possibly even weapons deployment, production, or storage sites.

In addition, satellite imagery can support verification missions at declared nuclear sites. In fact, satellites have played a central role in verifying key provisions of the SALT and START agreements, which has minimized the need for onsite inspections. More recently, satellites have also started to play a limited role for IAEA safeguards, where imagery can be used, in particular, to detect or monitor changes at safeguarded sites, which could then inform decisions about future onsite inspections. Beyond that, and relevant for arms control and disarmament verification, satellite imagery could be used to confirm the shut-down status of fissile-material production facilities or other sites formerly associated with a weapons program.

Satellite imagery as a verification technology also faces some fundamental challenges, however. Among them are equitable access to imagery, trust in the authenticity of the data, and the resources and capabilities to analyze the data, which given the volume of imagery will have to rely increasingly on machine-learning techniques. Today, only very few states or organizations have these expertise and capabilities, and research and training efforts could usefully focus on how these capabilities can be guaranteed for all relevant stakeholders so that satellite imagery can unfold its true potential as a verification technology. If the area of interest is not accessible on the ground, satellite imagery represents one of the few opportunities to gather almost real-time data over the area.

Wide-area environmental monitoring has been considered for more than thirty years as a technique to complement location-specific environment monitoring (“swipe sampling”), which has been part of the approved IAEA safeguards procedures since the late 1990s. Several recent advances in sensor technologies and platforms combined with advanced modeling capabilities and data analytics have further increased the potential of the technique. Still, the deployment of monitoring systems with global coverage for detection of undeclared activities such as spent fuel reprocessing or uranium enrichment remains impractical. WAEM may have more potential in a regional context.

The potential role of wide-area environmental monitoring for declared facilities is more limited. On one hand, environmental monitoring becomes much easier as the standoff to the emitter is reduced, for example, when sensors are placed at the site boundary or even onsite. At the same time, however, it may then be more straightforward to use other technologies to accomplish the same verification objective without inspector access. Perhaps the greatest weakness of traditional concepts of wide-area environmental monitoring is the reliance on one particular sensor or signature, say, krypton-85 to detect reprocessing. Suppressing a single indicator can therefore provide an effective countermeasure. Recognizing this shortcoming, modern approaches therefore envision data-fusion from multiple sensor platforms. It’s quite possible that this technique will make important contributions to national intelligence collection and analysis, but it’s more difficult to see now international organizations could leverage these approaches for treaty verification purposes.

Perimeter portal continuous monitoring has received relatively little attention as a verification technology. This is likely to remain true in the case of IAEA safeguards. Perimeter monitoring has been and will remain logistically complex and relatively costly. Relevant technical developments over the past two decades have been less significant than in many other areas. It is unlikely that new technologies will emerge that could fundamentally change this situation. Perimeter monitoring appears most useful for sites where military activities are allowed to continue, which could include nuclear weapons deployment, production, storage, and dismantlement sites. The complexity and costs of perimeter monitoring increase with the areas and number of sites that are monitored. Perimeter systems could be particularly attractive if only few sites with small footprints require monitoring. Perimeter control could therefore be a viable option to consider for situations where these conditions are met. Overall, a better understanding of the potential of perimeter monitoring would be valuable and may deserve greater attention of the arms control verification community.

Nonconventional verification approaches combining different technologies offer another and perhaps even particularly promising strategy to complement or reduce the relevance of onsite inspections. Often, these approaches may not require major innovations, but they have so far not been used or combined for verification purposes. One example highlighted in the discussion are "secure virtual inspections," where inspectors follow an inspection remotely but can still draw meaningful conclusions about treaty compliance. Such approaches may benefit from recent advances in cryptography and secure transmission of digital data any may offer great potential in reducing the need for routine inspections.

Intrusive onsite inspections in nuclear arms control have been a feature and privilege since the 1990s, but only the United States and Russia have implemented them on a routine basis. Other potential parties have less experience and may be more reluctant to agree to such inspections, especially early on. It is therefore prudent to emphasize R&D and training efforts in directions that limit onsite inspections to what is deemed absolutely necessary, i.e., where a similar level of confidence cannot be achieved through other verification measures. This chapter has offered a few examples where remote and standoff monitoring technologies and approaches could help to minimize onsite inspection activities to some extent without compromising the effectiveness of verification.

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